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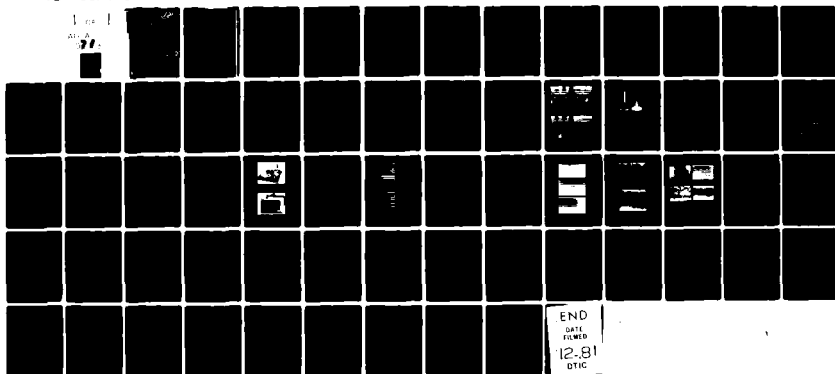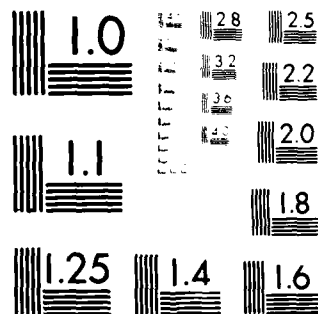   OCT 80 E C OWENS, H W MARBACH, E A FRAME   DAAK70-79-C-0175
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EFFECTS OF ALCOHOL FUELS ON ENGINE WEAR

INTERIM REPORT
AFLRL No. 133

By

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Ethanol	

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Research into the effects of alcohol on engine lubrication and wear has in-
vestigated four alcohol-containing fuels: pure methanol, pure ethanol,
methanol in unleaded gasoline, and ethanol in unleaded gasoline. This re-
search work has indicated that during low-temperature engine operations such
as winter commuter service and warmup, use of pure methanol may result in
increased engine wear. This increased wear appears to be primarily a low- →cont

20 ABSTRACT (Cont'd)

temperature problem. With the engine warmed to normal operating temper-
atures, this increased wear has not been observed.

To this point, the research with ethanol-containing fuels has not detected
any wear increases. This may be due to the short duration engine tests
being conducted, but nevertheless indicates that increased wear should be
of less concern with this fuel.

Wear mechanism studies have indicated that corrosive attack within the
piston ring and cylinder area by alcohol combustion byproducts is partially
responsible for the increased wear. Investigation of alcohol and lubricant
compatibility and physical removal of the lubricant films by liquid alcohol
have provided additional insights into these wear phenomena.

FOREWORD

This work was conducted during the period September 1976 through September 1980 and was funded by a DOE-DOD Interagency Agreement No. E(49-28)-1021 originated by the U.S. Department of Energy, Alternate Fuels Utilization Branch. The work directives and direct contract arrangements with U.S. Army Fuels and Lubricants Research Laboratory (USAFLRL) were made via contracts DAAK70-78-C-0001 and DAAK70-79-C-0175, issued by the U.S. Army Mobility Equipment Research and Development Command, Energy and Water Resources Laboratory, Ft. Belvoir, Virginia. The DOE technical monitor was Mr. E. E. Ecklund and the USAMERADCOM technical monitors were Messrs. F. W. Schaekel and J. V. Mengenhauser.

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INTRODUCTION

A national desire to reduce the volume of imported petroleum has generated a great deal of interest in the use of alcohols as fuels for spark ignition engines. Methanol, which could be derived from the United States' vast coal resources, appears to be an attractive liquid fuel. Also, much interest exists in the production of ethanol from agricultural products for use as a gasoline extender and blending agent.

While large amounts of data have been accumulated on the combustion aspects of these alcohols as fuels, the effects of methanol and ethanol on engine durability have had limited investigation (1-5)*. As a result, the U.S. Department of Energy, in conjunction with the U.S. Army, funded an investigation into the effects of these alcohols on engine lubrication and wear.

BACKGROUND

While alcohols--methanol and ethanol in particular--have been considered for and sometimes used as automotive fuels almost since the beginning of the automobile, usage has been restricted to periods of emergency or racing. During these periods, little attention has been given to alcohol effects on engine wear and deposits. While general references have been made to increased wear, only a few quantitative results have been reported in the literature, and the majority date into the 1930's (1, 2, 3, 5). Obviously, engine metallurgy and particularly oil formulations have changed considerably in the past 50 years. However, the same wear-inducing processes are involved in the combustion of alcohol in current engines. Incomplete combustion products of alcohol found in the blowby gases contaminating the engine oil sump contain organic acids and aldehydes which can increase corrosion, particularly under conditions of moisture condensation. Additionally, since alcohol contained in the blowby is polar, it would be expected to react with many of the lubricant additives and thus interfere with the inhibitors normally available to control engine deposits and wear.

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* Underscored numbers in parentheses refer to the list of references at the end of this report.

The current interest in methanol and higher alcohols is for their use as a replacement for petroleum-derived fuel supplies. Therefore, the lubricant-related problems which had been ignored or tolerated in periods of dire necessity must now be addressed and solved before alcohol can be considered a practical fuel for general consumer usage. During the past 5 years, as alcohol has again become a serious contender as an alternate automotive fuel in the United States, some initial studies of the effects of alcohol-containing fuels on engine lubrication have been undertaken. The work reported here was funded by the United States Department of Energy to ascertain the effects of alcohols, particularly methanol, on wear- and lubricant-related deposit formation, and if problems exist, to aid the development of lubricant additives or lubricant formulations to control these deleterious effects.

EQUIPMENT AND TEST PROCEDURES

Except for the radioactive tracer work, the test engines used in this work were Coordinated Lubricants Research (CLR) single-cylinder engines. The engine characteristics are summarized in Table 1. The engines were coupled to

TABLE 1. COORDINATED LUBRICANTS RESEARCH (CLR) ENGINE CHARACTERISTICS

Displacement	42.5 in.^{3}
Bore and Stroke	3.80 in. x 3.75 in.
Compression Ratio	8.3:1
Piston	Aluminum, 3-Ring
Piston Rings	1st Comp., Barrel-Faced Chrome; 2nd Comp., Taper Face Cast Iron; Oil Control; Two Chrome Rails and Expander
Cylinder	Replaceable Cast Iron Sleeve
Oil Capacity	1 Quart (no filter)
Main Bearing Insert	Labeco Part No. 8252 STD
Connecting Rod Bearing	
Big End	Labeco Part No. 8273 STD
Little End	Labeco Part No. 8301

appropriate cradled eddy current dynamometers to provide the necessary load control, and engine cooling was provided by tube-in-shell heat exchangers. Air-fuel ratio control was obtained by modifying single throat down-draft carburetors by installing tapered needle valves in the main fuel jet. These

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needle valves could be adjusted during engine operation as needed to set the desired equivalence ratio. Separate carburetors were used with alcohol and gasoline due to the large difference in required fuel flow rate.

An intake manifold heating system was initially installed in the manifold of the alcohol-fueled engine to raise the fuel mixture temperature to that obtained with unleaded gasoline. This heating system consisted of a finned aluminum heat exchanger downstream of the carburetor, an electrical heating element imbedded in the heat exchanger, an iron-constantan thermocouple near the intake valve, and a proportioning controller to regulate the mixture temperature. Use of this system was later discontinued when it was found that heating the intake air did not appear to affect engine wear.

Again except for the radioactive tracer work, engine wear was determined by two methods. Before each test, the engine was assembled using a new cylinder liner, piston, ring set, bearing inserts, and gaskets. The metallic component dimensions of interest were measured at that time. The valve stems, valve seats, and valve-to-guide clearance were also checked with these components being replaced as necessary to maintain proper clearances. Upon completion of the test, all of these components were removed from the engine, rated for deposits, cleaned, and measured. The dimensional changes were assumed to be the result of wear.

During the test, periodic samples of the engine oil were removed and analyzed to determine the concentration of wear metals present. Since these particles must have originated from various engine components, these measurements gave an indication of the metal removal rate integrated over the test duration. These measurements were felt to be more sensitive than the dimensional checks. However, they were nonspecific in that metal removal could be detected but the removal location and removal mechanism could not be ascertained.

The reference gasoline complied with Federal Specification VV-G-001690A and was purchased from a local refiner. Typical inspections are given in Table 2. The methanol fuel was purchased in 55-gallon drums as technical grade methanol meeting Federal Specification O-M-232d grade A. The ethanol used was BATF

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TABLE 2. UNLEADED GASOLINE PROPERTIES

Property	ASTM Test Method	VV-G-001690A Unleaded
Gravity, °API	D 287	56.8
Reid Vapor Pressure	D 323	8.4
Distillation, °F(°C)	D 86	
IBP		99(37)
10% evap		135(57)
20% evap		161(72)
50% evap		228(109)
90% evap		328(164)
EP		373(189)
Recovered, %		98.0
Residue, %		1.0
Loss, %		1.0
Gum, mg/100 ml	D 381	
Unwashed		6.7
Washed		0.3
Sulfur, wt%	D 2622	0.006
Lead, g/gal.	AA	0.03
Phosphorus	XRF	nil
Aromatics, % (FIA)	D 1319	30
Olefins, % (FIA)	D 1319	3
Research Octane No.	D 2699	93
Motor Octane No.	D 2700	84

specially denatured formula 28A (100 gallons anhydrous ethanol plus 1 gallon unleaded gasoline). Even though large quantities of alcohol were used during this program, this alcohol was procured in drums to preclude problems of water absorption which may occur in bulk delivery and storage. All the drums were stored in a covered area and kept sealed until ready for use. After the drum was opened and connected to the in-house fuel supply system, the air vent was connected to a "Drierite" cylinder to exclude moisture.

The reference or baseline lubricant chosen (Oil Code A) was a 10W-30 grade product qualified under MIL-L-46152 and API SE/CC. Since the oil had recently been used in an extensive field test, data existed to document the field performance level. Table 3 shows the new oil analyses.

The majority of engine test procedures used in this research program are based

TABLE 3. ANALYSES OF TEST LUBRICANTS

Lube Code Properties	A 10W-30	B 10W-30	C 10W-30	D 10W-30	E 5W-20	F 30	G 10W-30	H 10W-30
Kin. Viscosity, cSt								
at 40°C	68.9	71.8	67.7	67.5	26.3	106.0	71.8	56.0
at 100°C	11.7	11.0	10.4	11.2	5.9	11.8	11.8	9.95
V. Index	165	143	140	159	179	99	160	166
TAN (D 664)	2.5	1.7	2.7	2.5	0.2	2.0	2.4	3.0
TBN (D 664)	9.7						8.0	6.3
TBN (D 2896)	10.9	8.3	6.3	7.9	7.8	10.7	10.3	7.1
°API at 15.5°C(60°F)	28.4	30.3	30.1	28.9	21.2	27.8	28.0	31.2
Sulfated Ash, wt%	1.37	0.99	0.96	1.00	1.45	1.41	1.41	1.05
Elements, wt%, AA								
Barium	Nil	Nil	Nil	Nil	0.91	Nil	Nil	Nil
Calcium	0.38	Nil	0.23	0.08	Nil	0.35	0.37	0.24
Magnesium	Nil	0.11	Nil	0.12	Nil	Nil	Nil	Nil
Phosphorus	0.17	0.14	0.14	0.11	Nil	0.08	0.17	0.13
Sulfur	0.47	0.36	0.37	0.40	0.02	0.23	0.46	0.33
Zinc	(0.14)	(0.20)	(0.16)	(0.13)	Nil	(0.13)	(0.17)	(0.14)

( ) Denotes XRF method.

on various American Society for Testing and Materials (ASTM) oil evaluation test sequences. These sequences were designed to correlate laboratory oil performances with field experience. As such, they represent well established and widely recognized testing procedures that have some relationship, possibly tenuous, to actual vehicle/engine operations in consumer service.

DISCUSSION OF SCREENING RESULTS

Radioactive Tracer Engine Tests

A 350-cu in. Oldsmobile engine was mounted on the radioactive tracer stand and instrumented to obtain pertinent operating parameter data. The engine was set

GAMMA RAY
SPECTROMETER

DETECTOR

SUMP

WELL

TIME

PUMP

CPM

RECORDER
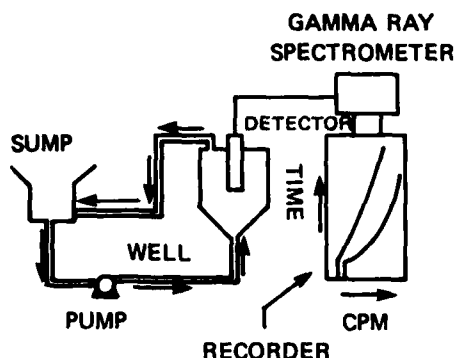
FIGURE 1. TYPICAL RADIOACTIVE
TRACER (Dual Isotope Measurement)

up for ASTM Sequence IIC operating condi-
tions(1) except that cooled valve covers
were not installed. A set of eight chrom-
ium-plated top compression rings were
irradiated. These top piston rings have
chrome ^{51} (face of ring) and iron ^{59} (side
of ring) which enables the measurement of
ring face and side wear simultaneously due
to the presence of two distinct radio-
isotopes and the ability of the instrument
to distinguish between them. The special
radioactive tracer oil sampling system was installed (Figure 1) which per-
mitted continuous readout of the wear rate of the radioactive components.
The Oldsmobile engine, equipped with standard (nonradioactive) rings, was
operated through a break-in sequence of gradually increasing speed and BMEP.
The carburetion was then optimized for the two test fuels (10 percent metha-
nol in gasoline and 100 percent methanol) by increasing the carburetor jet
sizes to accommodate the higher fuel flow rates. Performance of the test
fuels was considered optimized when the same power output for gasoline was
obtained at approximately the same manifold vacuum (or throttle setting) with
comparable exhaust temperatures. Spark timing was kept at the factory-recom-
mended setting, and no change in spark plug heat range was required. For the
initial sequence of tests, a high-power, high-speed condition of 75 kW (100
hp) at 3000 rpm, with 88°C (190°F) water jacket and 104°C (220°F) oil sump
temperatures was selected. This condition was to simulate high-output con-
ditions such as highway operation or trailer towing.

Following these procedures, the radioactive rings were installed, and the
engine was reassembled. Only six radioactive rings were installed to keep
the radioactivity at a level acceptable to the sensitivity of the gamma ray
spectrometer. A brief break-in sequence for the rings was then initiated.
During the break-in of the engine equipped with the radioactive rings, the
engine exhibited severe bearing knock and was quickly shut down. Examination
revealed that the No. 3 rod bearing and journal had failed. The engine was

disassembled on the stand, all piston assemblies removed, and the components thoroughly cleaned. The crankshaft and rod were replaced, and as a precaution, the piston and rings were replaced. The engine was then reassembled with six sets of radioactive rings installed. Break-in operations were restarted using the radioactive wear metals generation rate as an indicator of the progression of the run-in procedure. After operation for several hours with a stable wear rate, the initial series of baseline tests with unleaded gasoline was begun.

The results of all tests are presented in Table 4, and the face wear rates are illustrated in Figure 2. Six baseline tests were conducted, followed by two

TABLE 4. RELATIVE PISTON RING WEAR RATES

| Test No. | Test Fuel | Corrected Relative Wear Rates, cpm/hr[1] | |
		Chromium Face	Iron Sides
1	Gasoline	5,822	900
2	Gasoline	3,485	630
3	Gasoline	3,885	99
4	Gasoline	3,480	394
5	Gasoline	5,656	1,004
6	Gasoline	4,139	327
7	10% Methanol	4,116	968
8	10% Methanol	3,669	555
9	Gasoline	4,753	551
10	Gasoline	8,384	541
11	Gasoline	22,634	472
12*	Gasoline	19,807	2,542
13*	Gasoline	26,940	2,513
14	Gasoline	39,274	3,489
15	Gasoline	34,845	4,233
16	Gasoline	24,998	1,844
17	100% Methanol	Nil	7,081
18	100% Methanol	Nil	12,557
19	Gasoline	8,408	5,402
20	Gasoline	6,249	5,327
21	100% Methanol	5,905	6,384

(1) Counts/minute (cpm) is a linear function of the amount of radioactive wear debris accumulated in the engine oil; cpm/hr is a function of the rate of radioactive component wear.
* With Oil Number 2.
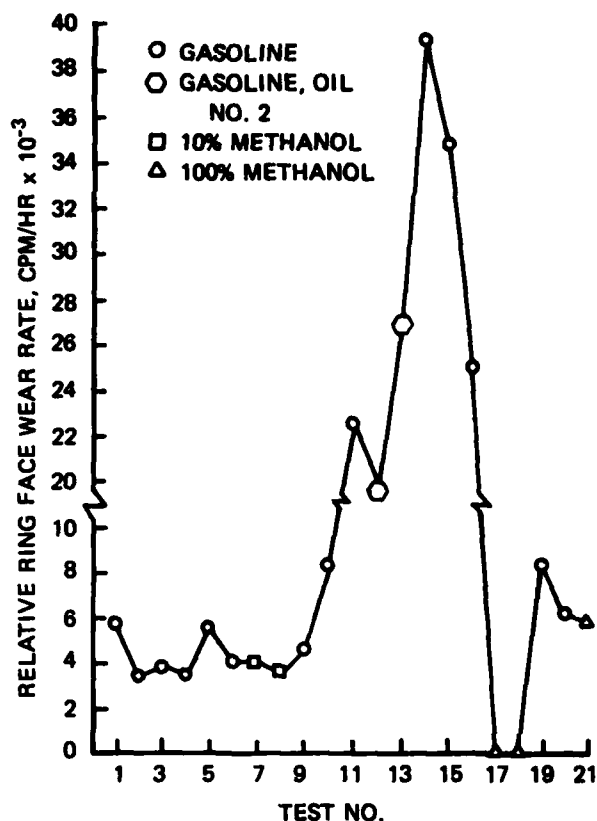
FIGURE 2. RELATIVE RING FACE WEAR RATES
BY TEST NUMBER

tests with the 10 percent methanol/gasoline blend. Of the six baseline tests, four demonstrated good repeatability of chrome face wear rates, but Tests 1 and 5 had higher wear. The iron side wear was erratic. This situation has been observed before, and it is theorized that wear particles collect in the ring groove and are flushed out at irregular rates. The two tests with 10 percent methanol (Nos. 7 and 8) produced repeatable face wear results which were no higher than the results from several of the baseline tests. Side wear was again highly variable, but in the same range as the baseline data. It was therefore decided to forego further testing and recheck the baseline with one or two tests prior to proceeding with 100 percent methanol.

The first baseline recheck (Test No. 9) gave wear rates that were about equal to the average of the initial baseline values. However, Test No. 10 resulted in a face wear rate approximately twice this average. This increase prompted a third baseline test (No. 11), which produced a face wear rate about five times higher than the average of the original baseline. Side wear remained nominal throughout these three tests, and there was no indication of any mechanical problem in the engine. Values of all pertinent operating parameters were virtually unchanged from previous tests.

The next two tests (Nos. 12 and 13) were performed with gasoline and a dif-

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ferent oil (a MIL-L-2104C grade 30 designated as Oil No. 2). Use of this oil seemed to slow the test-to-test increase in face wear (although still very high), but side wear increased by a factor of five over the average value of previous tests.

Test Nos. 14 and 15 were conducted with gasoline and the original oil. Both face and side wear rates increased dramatically over the average of the two previous tests with Oil No. 2; the increases were over 50 percent. Both tests were characterized by continuously increasing wear rates, as opposed to the generally stable wear rates that were obtained in other tests.

The test results indicated that fuel employed is not a factor in the wear phenomenon observed which appeared to be one of engine-lubricant interaction. The results obtained early in the test sequence with the 10 percent methanol/ gasoline blend clearly show that wear rates for this fuel were not increased relative to the six baseline tests that preceded these tests or to the two baseline tests that followed them. The unexpectedly high ring face wear rates, much greater than the average 4×10^{-3} cpm/hr normally expected, prompted a series of baseline gasoline tests to establish some performance pattern. Baseline wear rate of the chromium-plated ring face peaked in Test No. 14, then declined in Tests No. 15 and 16. Ring side wear in Test No. 16 was also substantially lower than the preceding two tests. As a result of this apparent reversal in the pattern of increasing ring wear, two tests (Nos. 17 and 18) were conducted with pure methanol. The ring face wear was so low as to be essentially zero, while side wear was several times greater than any previously observed.

These unusual results prompted an additional pair of baseline tests (Nos. 19 and 20). Face wear was definitely present, but lower than in the baseline tests conducted just prior to the methanol tests. Side wear was below that of methanol, but was still higher than in any previous baseline test. The good repeatability of results in these two tests suggested that wear rate had stabilized, so Test No. 21 was performed with 100 percent methanol. The face and side wear for this test were very close to the previous baseline values.

In analyzing these results, several points should be made. First, the variability in baseline wear rates continued to be rather large. The highest such wear rate was about eleven times greater than the lowest. This variation, together with the small number of results obtained with methanol, made a statistical correlation between wear rate and fuel type impossible. However, the face wear rates obtained with methanol were certainly no higher than most of the rates obtained with gasoline in this speed and load cycle.

The test engine continued to operate normally, with nominal values of all pertinent operating parameters. The cylinder bores were examined with a bore scope and found to be in good condition, without unusual wear patterns. Blowby flow rates had been measured on two occasions about two weeks apart with identical nominal results for this engine operating at relatively high-speed load. It is therefore concluded that the engine was not suffering from a mechanical problem such as broken rings. Post-testing disassembly confirmed this.

The phenomenon responsible for this variability of results was very possibly incipient ring scuffing of one or more of the radioactive rings. This scuffing could well have been a result of the earlier bearing failure. Because of the sensitivity of the method, such scuffing may not have been observable at disassembly. Whatever the cause, this lack of repeatability seriously compromised the results. Due to insufficient time for new parts to be obtained, further testing with the engine was halted.

The remainder of this report deals with various engine tests conducted in the CLR engine using a variety of test cycles, fuels, and lubricant formulations. A summary chart with a synopsis of the results of all these tests is included as Appendix A and will be referred to throughout the following discussion.

Wear Evaluation in the CLR Engine

Simulated ASTM Sequence IIC

For this program, two 50-hour test sequences were initially conducted with

the CLR engine. This test sequence was modeled after the ASTM Sequence IIC cycle which is normally used to evaluate the rusting and corrosion tendencies of motor oils. This procedure is described in Appendix B. The IIC test cycle was designed to relate to short-trip service under typical winter conditions in the upper midwestern United States. In modifying the test cycle for use with the CLR engine, the test speed was reduced by 100 rpm to 1400 rpm and the engine load, expressed as brake mean effective pressure, was held constant. The water jacket temperature was held at 43°C (110°F) outlet and the oil sump temperature was maintained at the specified 49°C (120°F). The engine was operated at these conditions for 15 hours per day until 50 total hours had been completed, 60 percent longer than the normal Sequence IIC cycle.

Test 1 was conducted using unleaded gasoline only. After-test inspections revealed light deposit levels and no measurable wear in the piston rings, bore or connecting rod bearings. The piston deposits rated 39 using the CRC diesel rating system. The diesel rating system was used instead of the more conventional spark ignition piston deposit rating method because it was felt that the diesel method provided better deposit discrimination in the piston ring and groove areas. Varnish was rated as lacquer. Used oil analysis revealed very little degradation (Appendix A, Pg. 3). Viscosity at 38°C (100°F) decreased by 40 percent during the first 15 hours, then decreased an additional 3 percent during the remainder of the test. This rapid initial loss in viscosity is normal and is attributed to shearing of the oil viscosity index improver additive. Both total acid and base numbers remained constant throughout the test, and the total water content of the oil reached 0.4 percent. In summary, the engine was in good condition with no evidence of wear or oil deterioration.

Test 2 was run using 100 percent methanol as the fuel. The air/fuel ratio was adjusted to the same equivalence ratio as the unleaded gasoline test and an intake air heater was used to maintain the same mixture temperature. The engine performed well with no signs of unusual combustion. At the first oil sample at 15 test hours, the engine oil was found to have a milky color, and analysis revealed that the oil contained 7 percent methanol and almost 8

percent water. However, the viscosity had not fallen as might be expected but was 75 percent higher than the 40 cSt at 38°C (100°F) established in the first test. Subsequent oil samples revealed a continuing increase in both the water and methanol content of the oil along with increasing viscosity. Analysis of the final drain sample showed the oil viscosity at 38°C (100°F) was 120 cSt, a 74-percent increase from the new oil and a 209-percent increase from the results of Test 1. The viscosity at 99°C (210°F) could not be determined because the methanol in the oil sample boiled. Total base number had dropped by two numbers while total acid number was unchanged. Upon standing for 2 to 3 days, the oil would separate into three distinct layers.

During the test, the engine oil accumulated both unburned methanol and water at an alarming rate. By the end of the 50-hour period, the "oil" contained 22 percent methanol and 18 percent water (Figure 3). This methanol/water content can be contrasted to a final water content of 0.48 percent when unleaded gasoline was used as the fuel, and the water produced by combustion of the two fuels is nearly equal. It is apparent that some mechanism other than the engine operation was responsible for this rate of lubricant dilution.

Upon disassembly, it was found that the entire engine was coated with a stable yellowish foam that varied from 1.3 to 5.1 cm (0.5 to 2 inches) in depth. Removal of the foam revealed no sludge or varnish deposits except in the piston ring zone area and the intake valve tulip, two relatively hot areas exposed
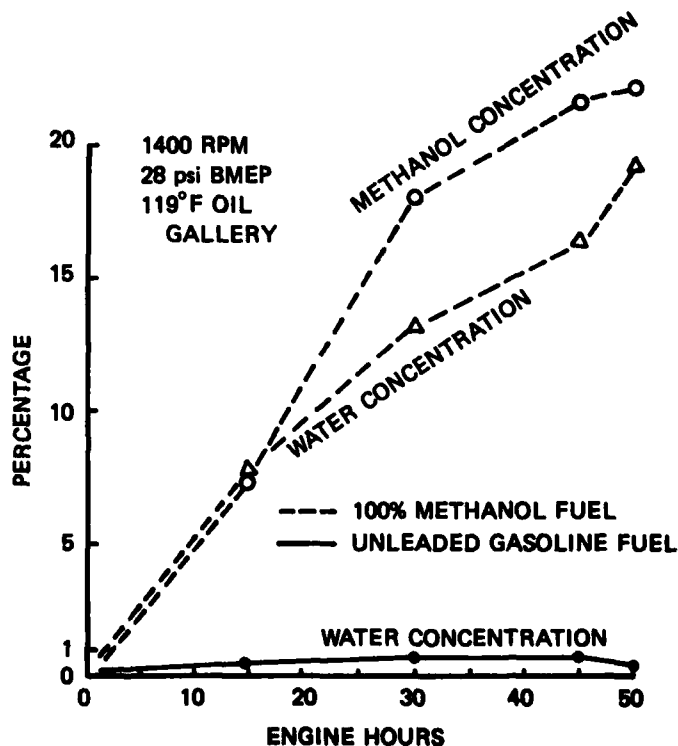
FIGURE 3. WATER AND METHANOL ACCUMULATION IN THE CLR ENGINE OIL

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to the oil (Figures 4, 5, and 6). These two areas were coated with a black tar-like deposit. Infrared analysis indicated that these deposits were not similar to the oil, but may be related to the oil's additive package. The methanol-fueled engine had considerably heavier piston deposits and had a CRC piston rating of 114. While this deposit level is greater than the 39 rating with gasoline, this is not an excessive level. Both compression rings were sluggish, although this had not affected the blowby flow rate. The chrome top compression ring gap increased 0.051 mm (0.002 inches) and the cast iron second ring gap increased 0.10 mm (0.004 inches). Neither the cylinder bore nor the bearing showed any significant wear. Apparently, 50 hours of operation were too short for extensive wear to develop.

It appears that methanol, when used in this type of cold operating cycle, collects in the engine oil and helps retain water in the oil as well. Deposit buildup as seen in this test could lead to stuck piston rings and restricted or stuck intake valves.

Simulated ASTM Sequence VC

Following this test, Continental Oil Company was contacted concerning its experiences using 100 percent methanol in the ASTM Sequence VC test (5). Representatives reported severe ring and cylinder bore wear in two Sequence VC tests, resulting in engine failures when using methanol. This wear was attributed to rust developing on the cylinder walls during periodic shutdowns. However, no discoloration of the oil or heavy piston deposits had been observed. The tests were conducted using Continental's 10W-30 grade MIL-L-46152 qualified product.

Based on this information and the fact that various field tests had failed to note any incidence of discolored oil samples, it was felt that the test cycle should include some period of higher temperature operation. The ASTM Sequence VC (Appendix C), normally used for rating motor oil sludge and varnish formation tendencies, was chosen because of the Continental Oil experience. Table 5 shows the operating conditions as they were scaled for the CLR engine. The 4-hour cycle shown is repeated four times per day followed by an 8-hour soak period.

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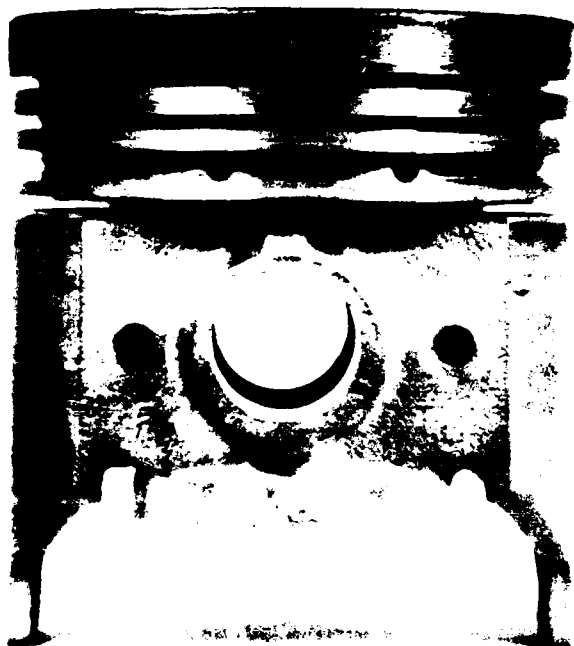
Test 1
Unleaded Gasoline

Test 2
100% Methanol

FIGURE 4. MODIFIED ASTM SEQUENCE II-C CYCLE CLR PISTON DEPOSITS – 50 HOURS
Front View
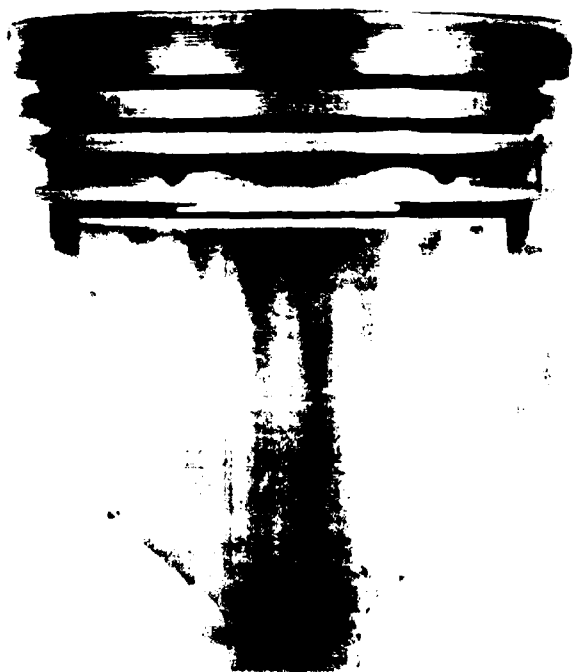
Test 1
Unleaded Gasoline
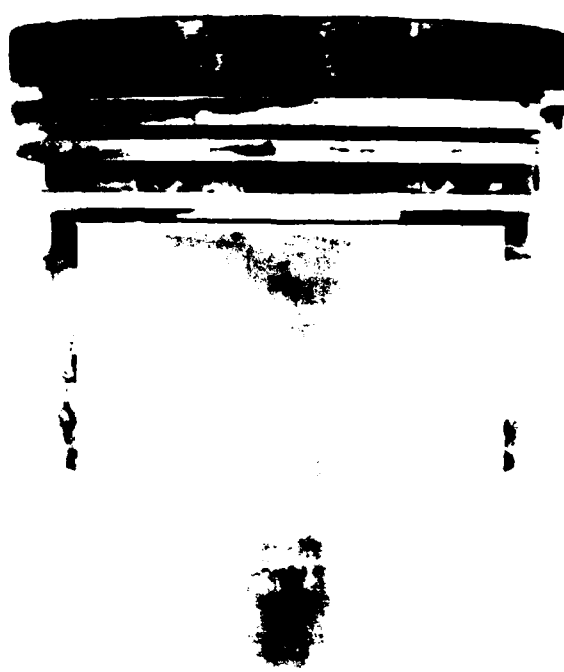
Test 2
100% Methanol

FIGURE 5. MODIFIED ASTM SEQUENCE II-C CYCLE CLR PISTON DEPOSITS – 50 HOURS
Anti-Thrust View

18
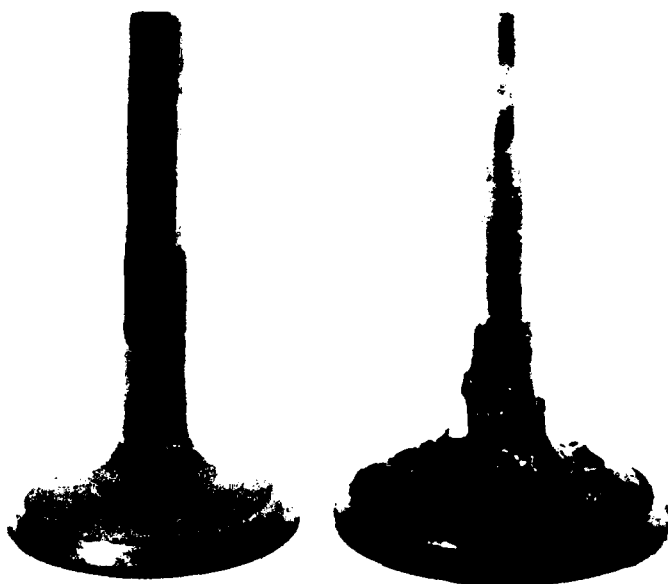
FIGURE 6.   VIEW OF CLR INTAKE AND EXHAUST VALVES DEPOSIT - TEST NO. 2
(Modified Sequence IIC Cycle - 50 Hours)

TABLE 5.   MODIFICATION OF ASTM SEQUENCE VC TEST OPERATING CONDITIONS DURING
STAGES OF EACH CYCLE

Condition	Stage I	Stage II	Stage III
Time, minutes	120	75	45
Speed, rpm	2500 ± 10	2500 ± 10	500 ± 10
Load, bmep, psi	92 ± 1	92 ± 1	11 ± 1
Oil Gallery Temp. °F	175 ± 5	200 ± 5	135 ± 5
Water Outlet, °F	135 ± 2	170 ± 2	115 ± 2
Carb Air Temp. °F	55 ± 2	55 ± 2	80 ± 5
Ignition Timing, °BTDC	28	28	6
Equivalence Ratio	1.1 ± 0.05	1.1 ± 0.05	0.8 ± 0.03

Note: Operating conditions shown are intended to be mid-range values.

A test using this sequence was started using 100 percent methanol as the fuel. The engine operated satisfactorily although some problems were encountered in maintaining both the 1.1 equivalence ratio and the required load. The discoloration of the used oil did not occur, but at approximately 65 hours into the test, a valve lifter began to stick and had to be replaced after 66 hours. The lifter was free of noticeable deposits, but the reed valve that admitted oil was sluggish and difficult to open. The engine was restarted, and the test continued until 100 hours was reached.

A series of five such simulated VC tests (numbered 3 through 7) were conducted with the CLR engine to establish a performance baseline with both 100 percent methanol and unleaded gasoline. Three of these tests (3, 5, and 6) used methanol, and the other two used unleaded gasoline as the fuel. They were all conducted with lubricant A. A summary of the results of these tests is presented in Table 6.

TABLE 6. SUMMARY OF INITIAL SIMULATED VC TESTS

	Unleaded			100% Methanol		
	min	avg	max	min	avg	max
Bore Wear, in.	0.0002	0.0002	0.0002	0.0001	0.00025	0.0004
Change in Ring Gap, in.						
Top Piston Ring	0.000	0.0015	0.003	0.002	0.002	0.002
2nd Piston Ring	0.002	0.0025	0.003	0.004	0.006	0.008
Change in Rod Bearing						
Weight	-0.0026	-0.0058	-0.0089	-0.0009	-0.0446	-0.1256
Wear Metals at EOT, ppm						
Fe	51	75	99	462	570	750
Cu	39	46	53	105	195	277
Cr	5	5	6	5	11	17
Change in Viscosity, %						
at 40°C	-34	-50	-64	-18	-20	-23
at 100°C	-35	-45	-55	-22	-25	-27
Change in TAN, D 664	-0.3	-0.2	-0.1	1.1	1.5	2.0
Change in Res. Oct., D 2896	-1.1	-2.0	-2.8	-1.0	-2.8	-4.6
Pent. Insols at 100 hr,						
w/coag, wt%	0.02	0.03	0.04	0.05	0.65	1.59
Benz. Insols at 100 hr,						
w/coag, wt%	0.02	0.025	0.03	0.10	0.48	1.12
H_2O at 100 hr, wt%	0.4	0.45	0.5	0.37	0.52	0.63

The iron and copper wear metals in the final (100 hour) oil samples were significantly different between the two fuels, and the test-to-test repeatability was good. The increase in iron wear with methanol fuel was partially reflected in wear of the cast iron second compression ring as evidenced by the increase in the end gap. There did not appear to be any difference in measured wear of the chrome-faced top compression ring. These results are illustrated graphically in Figures 7 and 8. It thus appeared that this test procedure differentiated between the two fuels in terms of wear. Also, there appeared to be no real change in bore wear, although some difficulty was encountered in measuring the area of the piston wall at top dead center (TDC).

Used oil analyses showed fewer differences than expected between methanol- and gasoline-fueled operations, other than the wear metals content. The oil viscosity did not decrease as rapidly with methanol fuel, similar to the viscosity results obtained in the simulated IIC operations. However, the water and methanol content of the used oil was negligible, and none of the emulsion formation evident in that earlier procedure was found. There was also a small increase in TAN with the methanol fuel. The change in insolubles was primarily due to one of the three engine test results and was not repeatable.

During the first methanol test, the upper piston pin bushing in the connecting rod failed. This was assumed to be an aberration and was ignored. However, on the second test of methanol, it was again noted that the used oil contained large concentrations of copper, and this upper piston pin bushing is the only copper-containing material within the engine. Further testing showed that this bushing failed a second time and was apparently being attacked when methanol was used as the fuel.

When the CLR engine was initially constructed for these tests, hydraulic valve lifters as presently used in many modern spark ignition engines were installed. However, during the first Sequence VC engine test, difficulty was experienced with these hydraulic valve lifters in that the fill valve in the

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FIGURE 8. SIMULATED VC PISTON RING WEAR

FIGURE 7. USED OIL WEAR METAL CONCENTRATION AFTER 100 HOURS

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lifters would stick and allow the lifter to collapse. The engine had to be stopped to replace the lifters. New hydraulic lifters were installed, and the engine was restarted. Within a short period of time, these new lifters had again experienced the same mode of failure. Finally, the hydraulic lifters were removed and replaced with solid lifters. Apparently, methanol was forming deposits which were leading to this lifter sticking as the observed problems have not occurred with gasoline.

As a result of this series of tests, this procedure was selected as an appropriate method for evaluating alcohol fuel effects on engine wear and for screening lubricant formulations.

Alcohol/Gasoline Blends and Ethanol

To evaluate the effects of alcohol-gasoline blends on engine wear, blended fuels containing either 15 percent methanol or 15 percent ethanol in unleaded gasoline were prepared. These fuels were then used to conduct extended duration VC-type tests in the CLR engine.

Because of the reduced concentration of alcohol in the fuel, the test severity was increased to produce observable differences between the various fuels. This severity increase could be achieved by decreasing the average engine operating temperature or by increasing the test duration. Increasing the test duration was felt more representative of field conditions than lowering the operating temperatures. This procedure also allowed comparison with the pure alcohol test results obtained earlier.

Test No. 20 was conducted using the 15 percent methanol blend while Test No. 21 used only unleaded gasoline to establish a baseline. Lubricant A was used in both tests. Post-test deposit ratings showed no significant difference in piston deposits with the methanol blend, indicating that low methanol concentrations may not reduce combustion chamber deposits. Wear measurements did not show any differences in piston ring, cylinder bore, or bearing wear between the two tests. However, wear metal content in the engine oil, supposedly a more sensitive wear indicator, showed a 35-percent increase in

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copper wear and a 60-percent increase in iron wear with the methanol blend.

The wear increase observed using the 15-percent methanol blend is particularly interesting because these wear increases are proportional to the wear increases experienced with pure methanol. Three tests using pure methanol fuel were performed with the same reference lubricant and test cycle as the 15-percent blend. These tests resulted in an averaged 280-percent increase in copper wear and a 735-percent increase in iron wear. Thus, 15 percent of these two averaged increases is a 42-percent increase in copper wear and a 110-percent in iron wear. These estimated values are close to the actual values of 35 percent copper wear and 60 percent iron wear obtained with the 15 percent methanol blend. Obviously, drawing such conclusions from only two tests leaves a large margin for error. However, these initial results may indicate that wear increases are in proportion to the methanol concentration.

While these are substantial increases, it is important to note that wear with methanol is apparently confined to periods of low temperature engine operation. These wear increases with methanol fuel blends may occur only during warm-up periods, particularly during cold weather operation. Therefore, the differences in wear rates when using the methanol blend may be undetectable in the field under most conditions. This wear increase could be considered acceptable until confirming field tests can be conducted.

Test No. 22 was completed using a blend of 15 percent ethanol in unleaded gasoline. This was the first test conducted using ethanol. There were no measurable differences in cylinder, piston ring, or cylinder bore wear between this test and the unleaded gasoline Test No. 21. However, in Test No. 22, the wear metal concentration in the used oil varied in an unusual way. The wear metals concentrations increased rapidly during the initial portion of the test, but stabilized, and in the case of iron, decreased during the remainder of the test. By the end of the test, the apparent wear rates were similar to those of unleaded gasoline. While this wear metal anomaly may be due to testing problems such as sampling errors, it raises a question of actual ethanol performance. The effects of ethanol on engine wear had never been examined for pure ethanol fuel.

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As a result, a 100-hour engine test, No. 24, using 100 percent ethanol as the test fuel, was conducted to evaluate the premise that ethanol behaves very similarly to methanol as far as engine lubrication and wear are concerned. Also, a second 240-hour test using 15-percent ethanol and lubricant D was conducted.

All these ethanol tests showed very low wear rates relative to the same type of tests with methanol. These wear rates, as indicated by wear metal concentrations in the oil, were essentially equal to those of unleaded gasoline. This is extremely interesting, particularly in the case of the pure ethanol, since this may indicate that with ethanol the problem of increased cylinder bore wear was not occurring. However, the copper content of the oil had increased with the ethanol fuels.

Lubricant Screening

With the establishment of a test procedure that appeared to distinguish between methanol and unleaded gasoline in terms of wear, the next activity concentrated on evaluating various lubricant formulations. Several lubricants were procured in preparation for testing. Table 3 lists these lubricants along with physical and chemical inspections. A 100-hour Sequence VC test (Test No. 15) was conducted using lubricant formulation B and methanol fuel. The results of this test appeared promising in that the iron wear metal concentration in the final oil drain was substantially less than that obtained in the previous tests with the base lubricant. However, this test was the first test during the program where significant lower connecting rod bearing wear occurred. In this 100-hour period, the bearing insert lost 0.015 grams in weight. This compared with an average weight loss of less than 0.001 gram throughout all the previous tests.

Following this test, a 100-hour VC test was completed with the base oil lubricant A and unleaded gasoline as the fuel. Test No. 16 produced no unusual results and helped reconfirm the baseline previously established. As shown in Appendix A, it appeared that the wear, as indicated by used oil wear metals content, was substantially below that of any of the preceding methanol-fueled tests.

As a result, further analysis was undertaken with lubricant B including a 50-hour endurance run at low temperature (Test No. 17) and a base case test with unleaded gasoline (Test No. 19). Using the low-temperature IIC cycle, the lubricant B still accumulated large quantities of methanol and water (8.4 percent methanol, 25 percent water at 50 hours) relative to Lubricant A. When disassembled, it was found that the entire engine was coated with a stable yellow/beige emulsion or foam (see Figures 9 and 10) similar to that accumulated in Test No. 2.

Lubricant C was evaluated using the 100-hour endurance test cycle, Test No. 18. This lubricant produced extremely high iron and copper wear metal concentrations in the oil; as a result, no further evaluations were conducted.

Next, Test No. 25 was conducted using lubricant E and 100 percent methanol. This lubricant contained a barium-based additive system. Also, this lubricant had been used successfully in the field in engines and in hydraulic power transmission fluids (HPTF) systems. Test No. 25 had the same bore wear as lubricant A, but it had a 60-percent reduction in iron wear metals in the oil when compared to the baseline tests using lubricant A and 100 percent methanol.

At this stage in the testing, a rusting problem was identified and will be discussed in the section on "Hardware Modifications."

Hardware Modifications

Test No. 27 was conducted using lubricant F, a MIL-L-21260B preservative lubricant which had shown some promise in reducing corrosion due to high-sulfur fuel. Test No. 28 used lubricant D, a magnesium-based lubricant. The completion of these two tests revealed a higher iron wear metal accumulation rate, but an average copper accumulation rate in the used lubricant. The wear metals accumulating in the used engine oil did not respond as expected to the variation in lubricant additive treatment. This appeared to indicate that a shift in the baseline wear rate may be occurring. Therefore, Tests No. 29 and 30 were conducted using the 10W-30 baseline lubricant A. Test No.
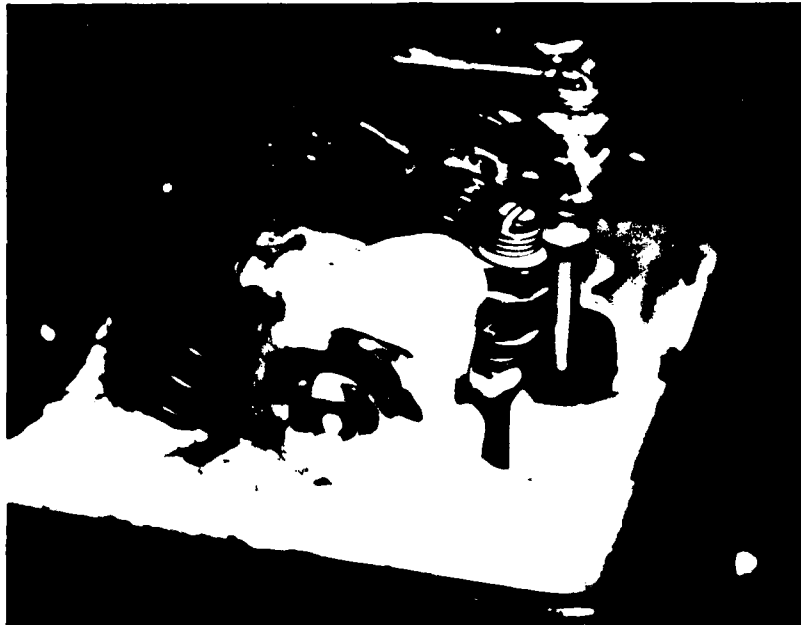
FIGURE 9.   CLR - ROCKER ASSEMBLY
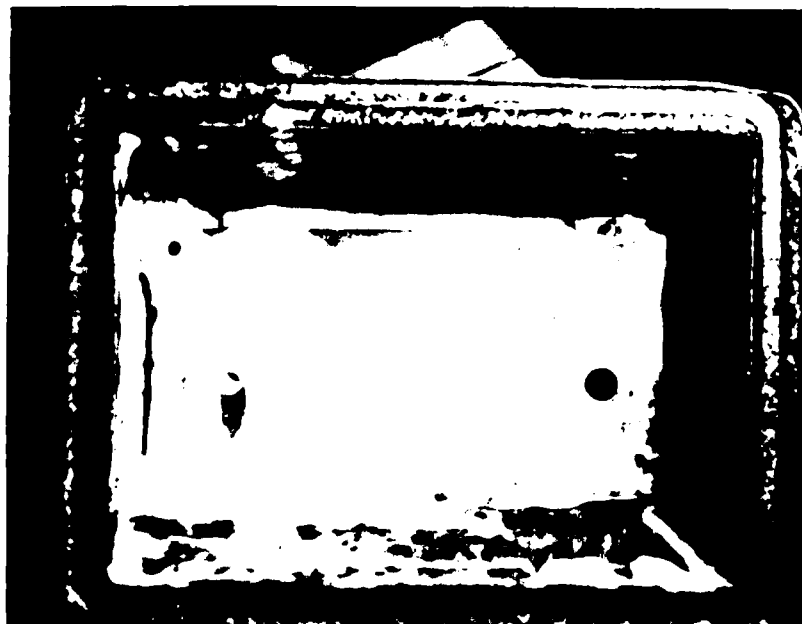
FIGURE 10.   CLR - ROCKER COVER

29 used unleaded gasoline, while Test No. 30 used 100 percent methanol fuel to re-establish the baseline. Test No. 29 had 100 hours (end of test) wear metals of 90 ppm iron and 67 ppm of copper. These levels fall between the high and low range for all the unleaded gasoline baseline tests. Test No. 30, using methanol, had 124 ppm copper wear metal, which is about the average for the methanol-fueled baseline tests; however, the iron wear metal accumulation rate approximated the previous methanol baselines through only 64 hours. Between 64 and 100 hours, the iron content increased even more rapidly. At the end of the test, the iron content was 200 percent higher than the highest previous methanol baseline test. This appeared to confirm a shift in the baseline wear rate when using 100 percent methanol. Further investigations indicated that corrosive attack and rusting in areas other than the cylinder bore were contributing to the accumulation of metals in the oil sump. Corrosion was observed in a variety of components used in the engine.

It was desired to determine the relative contributions of corrosion and rusting in various areas of engine to the total wear metals concentration. The rust formation appeared to affect the lower temperature areas of the engine such as the upper valve train and particularly the blowby removal and lubricant fill piping. Therefore, a substitution of stainless steel for iron components was made wherever possible in these areas. After the hardware modifications were completed, another methanol baseline test, No. 31, was conducted. At the end of the 100-hour test period, the test was continued because of low iron wear metals level, until 152 hours. Disassembly showed that piston scuffing had occurred on the full length of all four edges of the piston skirts and were 12.7 mm (1/2 inch) to 11.4 mm (3/8 inch) in width. This appeared to be due to faulty casting of the piston by the manufacturer. It was not certain if the low iron content of Test No. 31 could be attributed to the hardware modification or was piston scuffing related. Thus, another baseline, Test No. 32, was conducted which used the baseline lubricant A and 100 percent methanol. This test produced a 100-hour (EOT) iron level of 320 ppm which was 142 ppm below the previous lowest baseline. The results of Test No. 31 was thus apparently due to the piston scuffing, but the hardware modification had a substantial effect on the observed iron wear metals. These tests are summarized graphically in Figure 11.

28
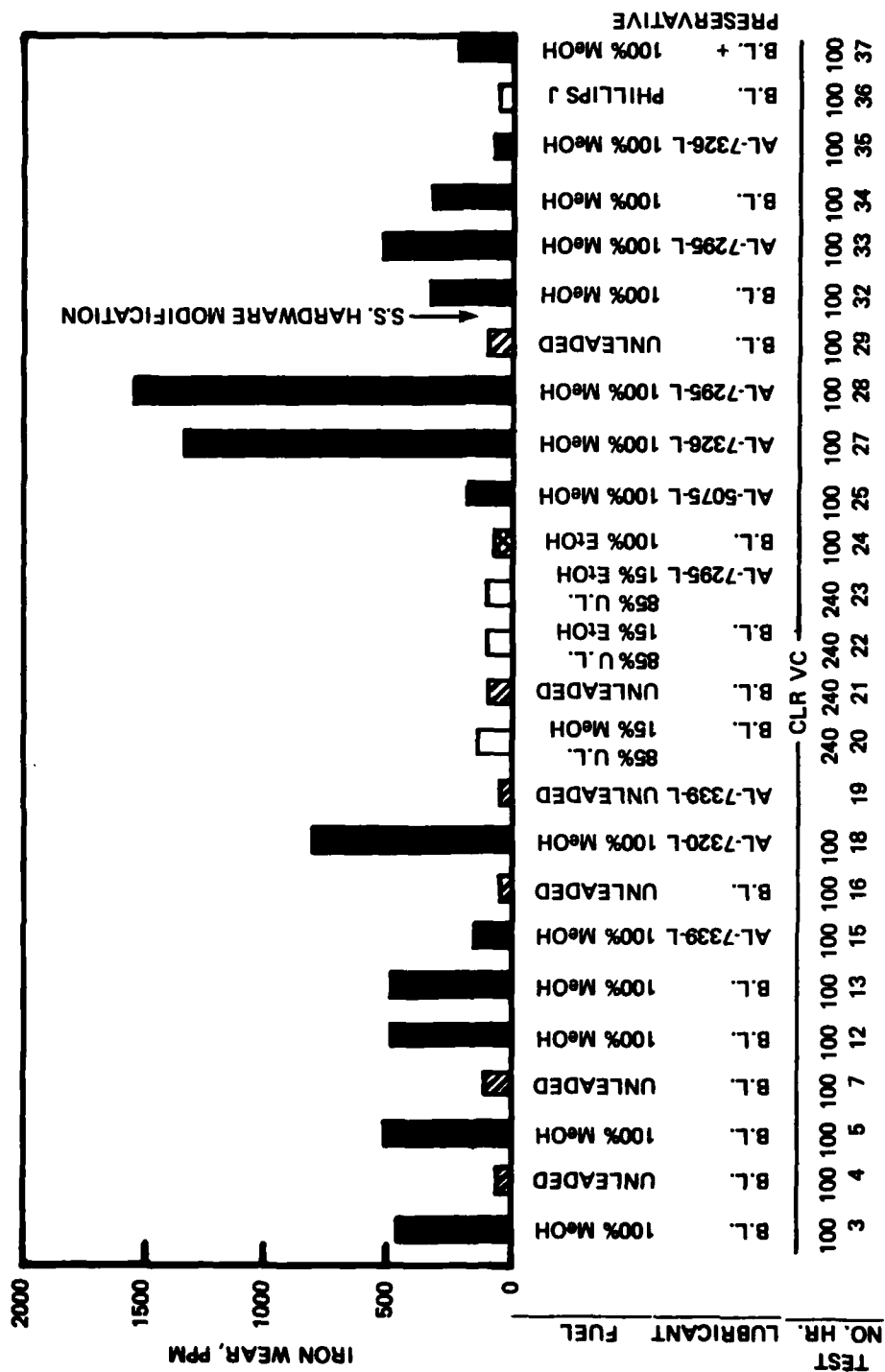
FIGURE 11. EOT IRON WEAR METALS

The oils of Tests No. 27 and 28 were rerun with 100 percent commercial grade
methanol as fuel with the new engine configuration. Test No. 33 used the
magnesium-based lubricant D and was a repeat of Test No. 28. Test No. 35 was
run using lubricant F and was a rerun of Test No. 27. From the results of
these tests, it appears that in the earlier tests corrosion and rust forma-
tion was contributing to the iron particle accumulation in the used oil. By
comparing the test results which used the stainless steel components (Test
Nos. 32 and 34) with the results early in the test sequences (Test Nos. 3, 5,
12, and 13), it appears that this mechanism was responsible for one-third of
the iron wear metals observed (Figure 11). This rust formation and corrosive
attack would be expected to occur in actual engine operation, and represent a
problem which must also be addressed in oil formulation and engine design.
However, this corrosion would be expected to be very design related. It was
felt that this additional source of iron particles interfered with the in-
vestigation of wear within the cylinder bore area and should be eliminated to
the extent possible through platings and material substitutions. This mini-
mization of rust areas means that any oil formulations identified or de-
veloped in this program may control wear but not rusting. This problem will
have to be addressed, perhaps by using a IID-type test procedure if methanol-
based fuels are to be introduced.

Since encouraging results were observed in Test No. 35, the preservative zinc
additive from lubricant F was added to the baseline lubricant A in the same
concentration as it appeared in lubricant F. This lubricant G was evaluated
in the 100-hour VC test using 100 percent methanol fuel. The preservative
additive did result in a wear metals reduction as can be seen in Figure 11.
The EOT wear iron level in the lubricant was reduced by only 35 percent from
the two previous baseline Test Nos. 32 and 34.

Test No. 38 was conducted on lubricant H using 100 percent methanol. This
lubricant is a multiviscosity MIL-L-2104C candidate and has performed quite
well in various engine testing. The wear metals accumulation levels for this
lubricant were increased by approximately 35 percent over the baseline Test
Nos. 32 and 34.

WEAR MECHANISM STUDIES

Three possible mechanisms have been postulated to explain the observed effects. (1) Methanol or its intermediate oxidation products may attack the metal surfaces in the ring zone, leading to corrosion and metal removal. (2) Because of the increased volume of fuel present and the higher heat of evaporation, incompletely vaporized methanol may accumulate on the cylinder walls and "wash away" the lubricant film. This would leave the surfaces unprotected and adhesive/abrasive wear would follow. (3) Methanol may react with the lubricant and its additive package and interfere with the corrosion protection normally provided.

Evidence of Corrosive Attack

The top and second compression rings from Test No. 6 using 100 percent methanol fuel, Test No. 7 using unleaded gasoline, and Test No. 8 using a 15 percent methanol in gasoline blend were visually examined under 32X and 400X magnification. These inspections indicated greater wear in the methanol-fueled engines, as evidenced by the wider wear band on the ring faces. The chrome-plated top rings from the engines appeared similar although there is a definite increase in intergranular cracking of the chrome plating with the methanol-fueled engine, particularly in the 100 percent methanol case.

Comparison of the cast iron second compression rings revealed major differences between the tests (Figures 12, 13, and 14). The ring from the gasoline-fueled engine showed a normal wear pattern. However, the wear surface of the ring from the 100 percent methanol-fueled engine appeared to have been etched. This corrosive attack is less evident but still detectable with the methanol-gasoline blend test. This corrosive attack of the rings appears confined to the rubbing area of the ring, and there was no evidence of significant corrosive attack in the noncontact or nonrubbing portions. This implies that a clean metal surface may be necessary for this attack to take place.
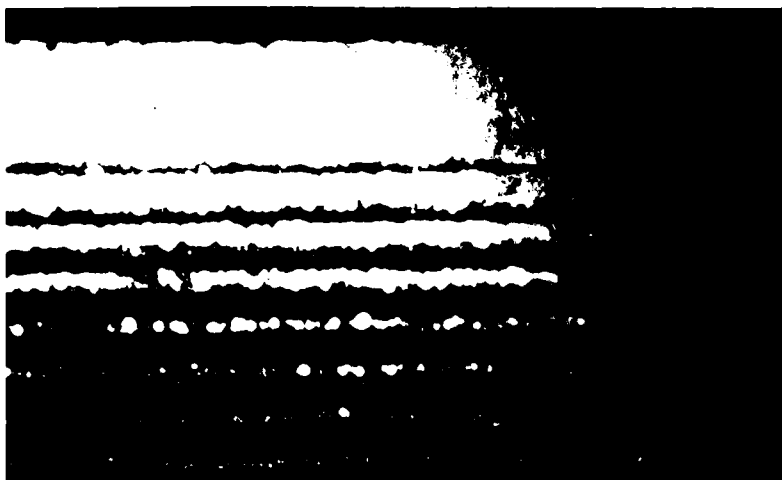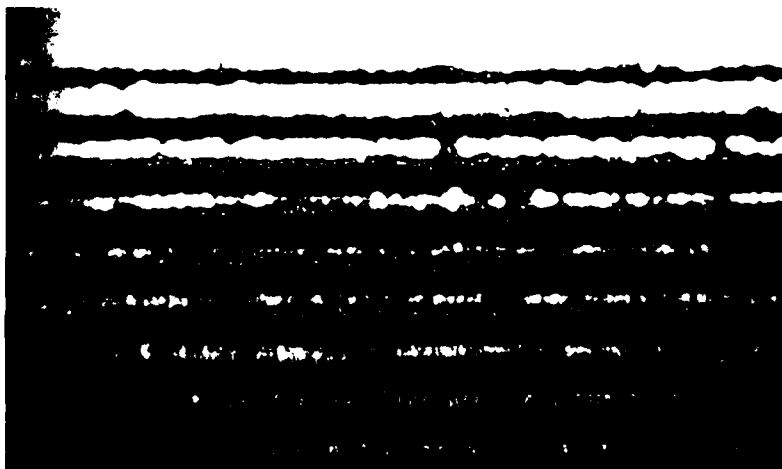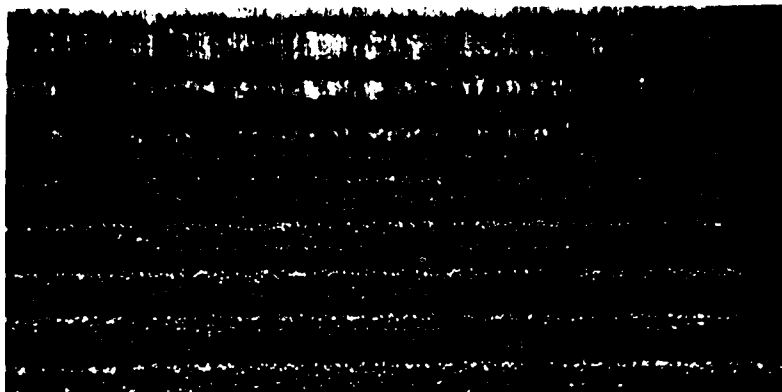
FIGURE 12. RING FROM METHANOL-FUELED ENGINE

a. Gasoline-Fueled Engine
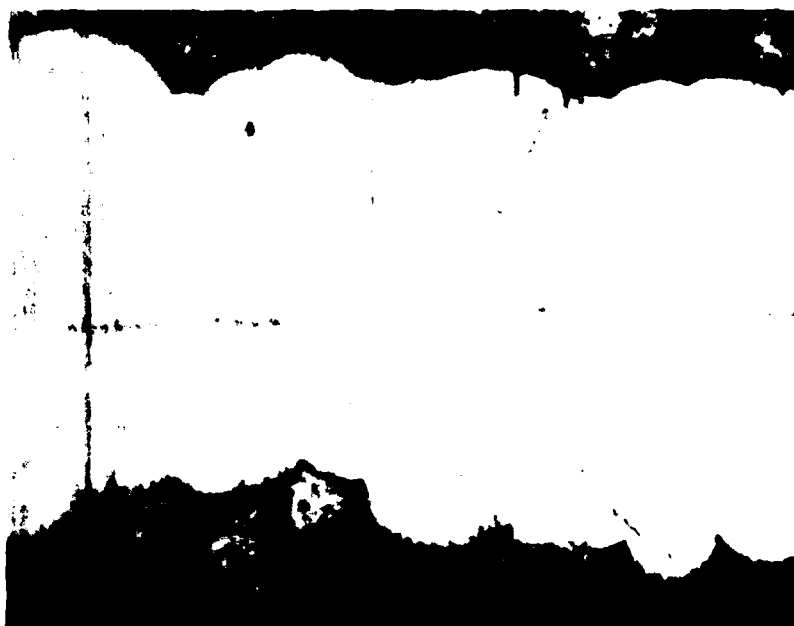
b. Methanol-Fueled Engine

FIGURE 13.   CHROME-FACED COMPRESSION RINGS
(400X Magnification)
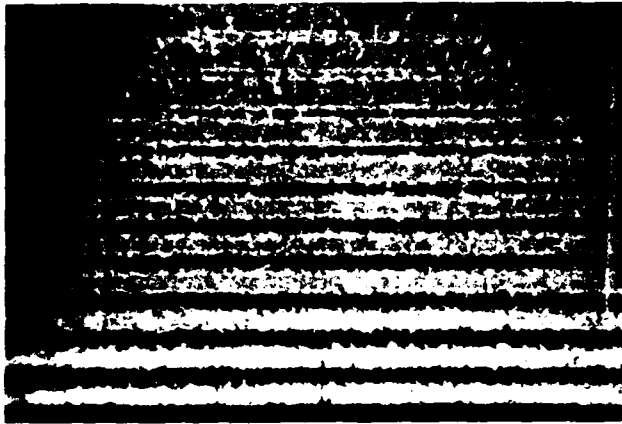
32X Magnification
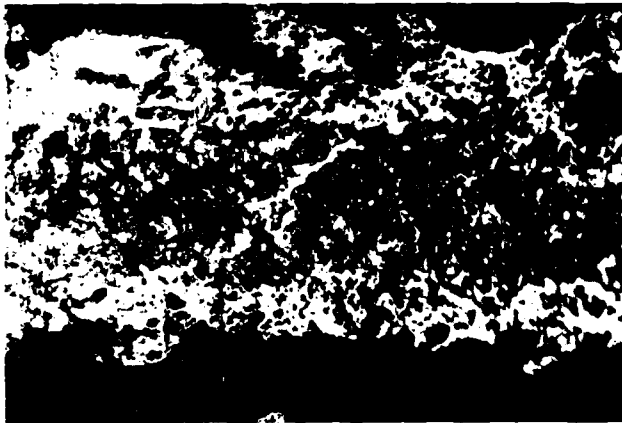
400X Magnification

METHANOL   UNLEADED GASOLINE

FIGURE 14.   MICROSCOPIC EXAMINATION OF CAST IRON RING WEAR SURFACE
(Photos reduced to 74% of original)

Common Sump Engines

Two CLR engines (Test No. 26) were configured so that they shared a common oil reservoir while they were operated. One engine was fueled with 100 percent methanol, the other with unleaded gasoline. Both engines had their internal oil pumps made inoperative and shared a common scavenged oil sump system using lubricant A. The initial oil charge for this system was 4.54 kg (10.0 pounds), or approximately three times the 1.40 kg (3.08 pounds) of oil normally required for a single engine. The two engines were operated at the same brake power levels as were used in the VC tests. This procedure resulted in a slightly lower indicated mean effective pressure (piston loading) due to the reduced friction loss when not using internal oil pumps.

It was hypothesized that if the methanol causes wear by degrading the lubricant, then both engines should wear equally. However, if there is a direct methanol attack or a "wall-washing" effect, then the methanol-fueled engine should show greater wear. During the test, the wear metals increased at a lower rate than was expected; at 384 hours, the wear metals levels were 312 ppm iron and 70 ppm copper. One hypothesis to explain the lower observed wear rate was that during the idle cycle, the lubricant is being reversibly degraded and contaminated by methanol with time. This process reaches some threshold at which point the engine begins to wear rapidly. As the engine oil is heated during the following test phases, the oil is restored to its initial condition, and the rapid wear is halted. This process is repeated at each idle cycle. Because of the increased lubricant volume of this test, there was insufficient time during the idle phase for rapid degradation to occur; therefore, the apparent engine wear was lower. At 384 hours, the 45-minute idle cycle was extended by 90 minutes to evaluate this hypothesis. The rate of iron increase up to 384 hours was approximately 1 ppm per hour and, after increasing the idle time, the next cycle indicated a wear rate of approximately 4 ppm per hour. Apparently, the increased idle cycle indicates that the reversible degradation and the increased lubricant volume hypothesis may be valid.

The wear metals at the end of test (461 hours) were 553 ppm of iron and 81
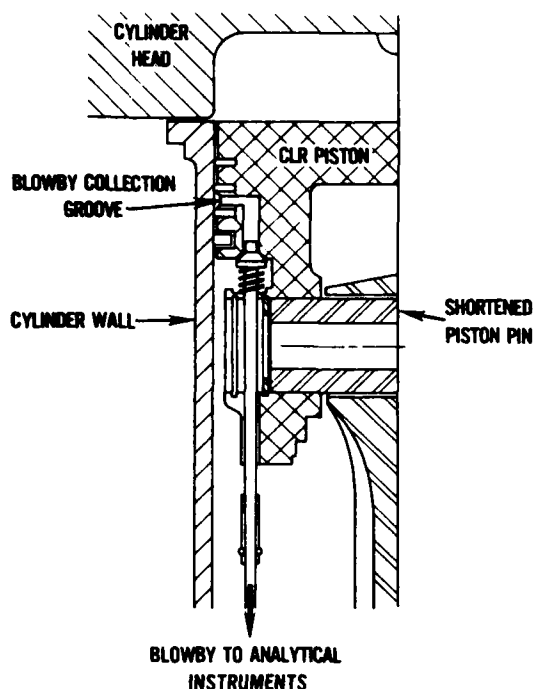
FIGURE 15. BLOWBY DIVERSION PISTON SCHEMATIC

ppm of copper. More wear was observed in the rings and cylinder wall area of the methanol-fueled engine. This higher rate of wear dispels the claim that lubricant degradation alone promotes wear. The results suggest that direct interaction, i.e., wall washing and/or metallurgical attack, is a major wear mechanism with lubricant degradation as an additional effect.

Blowby Diversion

Since it appeared that the combustion materials in the ring zone produced by the use of methanol were to some extent responsible for the increased wear in that area, a system for sampling the gases in the ring zone of the CLR engine was installed.(8) This sampling system, shown in Figure 15, consisted of a blowby expansion and collection chamber in the piston connected to the exterior of the engine via a sliding tube arrangement. The gases passed through this tubing to a collecting system located adjacent to the engine. The tubing located within the engine was brass, while the external tubing and associated plumbing was either Teflon® or stainless steel. Such a sampling system cannot assure a quantitative measure of the gases present in the ring zone since the combustion products may continue to react and change in composition during the extraction process. However, this system should nevertheless provide an indication of the original gas composition.

With the installation completed, the CLR was started on Test No. 9, using the modified VC sequence and 100 percent methanol as the fuel. Blowby samples were taken for analysis beginning at 13 and 98 test hours. At each sampling

point, two complete sets of samples were taken; one during the high speed portion and a second during the idle period. The blowby gas was passed through a series of three progressively colder condensers (0°C to -40°C) and the remaining gas collected in sampling bags. The contents of the condensers and bag were available for analysis.

The gaseous blowby was analyzed by gas chromatography for light hydrocarbons, by the DNPH (dinitrophenylhydrazone) method for aldehydes, and by standard exhaust gas techniques for unburned hydrocarbons, oxides of nitrogen, carbon monoxide, carbon dioxide, and oxygen. This gaseous blowby from the idle portion of the cycle was found to contain approximately 30 to 190 parts per million oxides of nitrogen, 2 percent carbon monoxide and over 4000 parts per million unburned hydrocarbons. DNPH analysis showed concentrations of formaldehyde as high as 440 parts per million with lesser quantities of higher molecular weight aldehydes. GC analysis of the gas also showed significant concentrations of methane, ethane, propane, and acetylene. The liquid condensate from the blowby was also analyzed for total acid number and by gas chromatography. Total acid number was in most cases higher during the 2500 rpm period than from the idle portion. Total acid numbers ranged between 0.6 and 2.5 except for one point of 23.9. The GC analysis of this condensate also showed concentrations of methanol, formaldehyde and acetic and formic acids in relatively low concentrations.

Vaporization

As a final example of this continuing mechanism study, an attempt was made to investigate the effects of preventing liquid methanol from entering the combustion chamber. When methanol is carbureted into the engine, there is a possibility that liquid droplets enter the combustion chamber or that liquid condenses on the relatively cold chamber walls. A CLR engine was fitted with both a carburetor and a methanol-vaporization system. The methanol vaporization system consisted of a boiler and a superheater section, both of which were heated electrically. When operating on the vaporization system, methanol vapor was supplied at the intake valve of the engine at a state with a sufficient degree of superheat to ensure that no condensation occurred in the

TABLE 7. OPERATING CONDITIONS FOR CLR TEST SERIES TR	
RPM	1550±25
Load	1.36±0.15 kW (2.5±0.2 Hp)
Air/Fuel Ratio	5.0±0.2
Oil Temperature	57°C(135°F)
Coolant Temperature	46°C(115°F)
Superheater Outlet Temperature	149°C(300°F)
Superheater Outlet Pressure	86 kPa(12.5 psi)

combustion chamber. Operating in this mode effectively prevents liquid methanol from collecting on the cylinder walls and "washing away" the lubricating film. Figure 16 is a schematic of the methanol vaporization system.

With this arrangement, two 50-hour wear tests were performed. In Test No. TR-1, the engine was fueled using the methanol vaporization system. In Test No. TR-2, the engine was fueled with neat methanol using a standard carburetor with primary jet control. Both tests shared the same set of operating conditions, listed in Table 7.

Figures 17 through 19 show the results of the oil analysis performed over the duration of each test. In the case of vaporized methanol test (TR-1), the water, methanol, and iron content of the lubricating oil remained constant. The results of the test using the carburetor (TR-2) showed large increases in the water and methanol concentration and no change in the iron content up to 36 hours. At 36 hours, the methanol concentration in the oil reached 18 percent, and the water content peaked at 43 percent, with the oil accounting for only 39 percent of the sump content. The presence of liquid methanol in the combustion chamber thus resulted in rapid lubricant dilution. At this point, the water and methanol concentrations began to decrease and the iron wear metals concentration began to increase rapidly. This wear increase may have been the result of poor lubricating quality of the oil-water-methanol mixture rather than any attack or action by the methanol alone. However, this result indicates that methanol fuel use can result in severe lubricant dilution at operating temperatures that are not unrealistic for cold weather operations. It is less clear that the state of the methanol-air mixture entering the combustion chamber is important in the observed wear, since there was little difference in wear between the two engine tests until the 36-hour point.
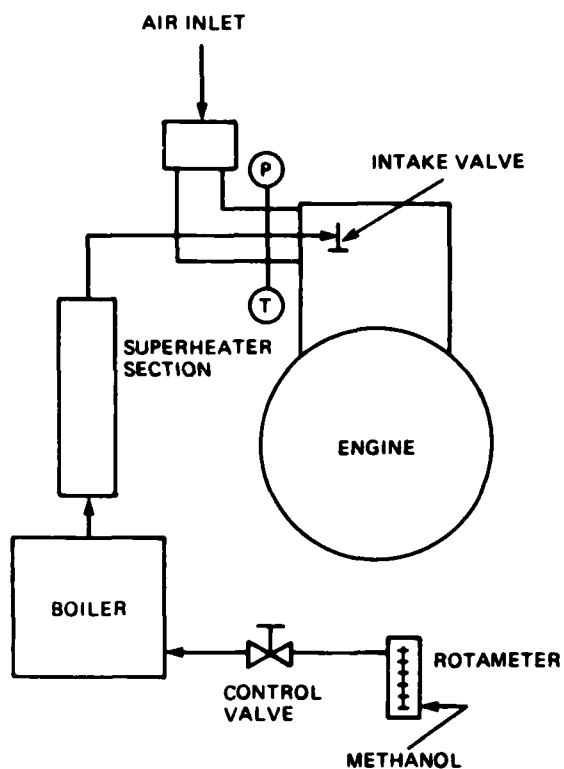
Fig. 16 – Methanol vaporization
system schematic
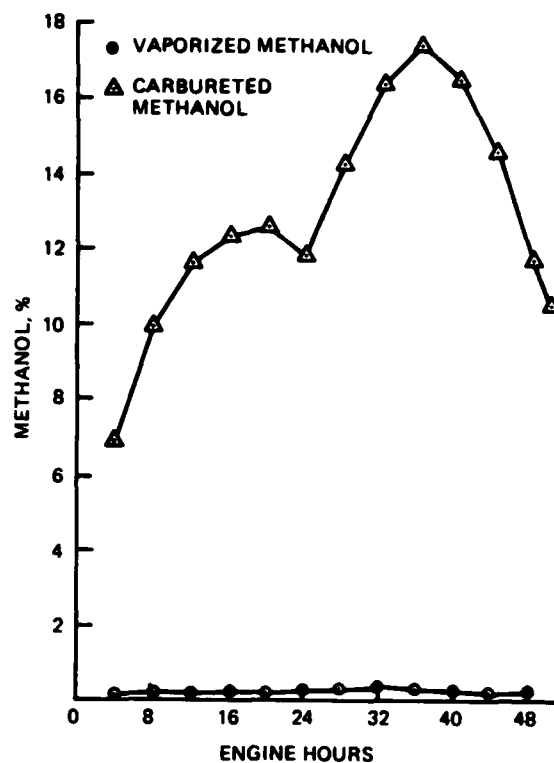
Fig. 17 – Methanol concentration
in lubricating oil
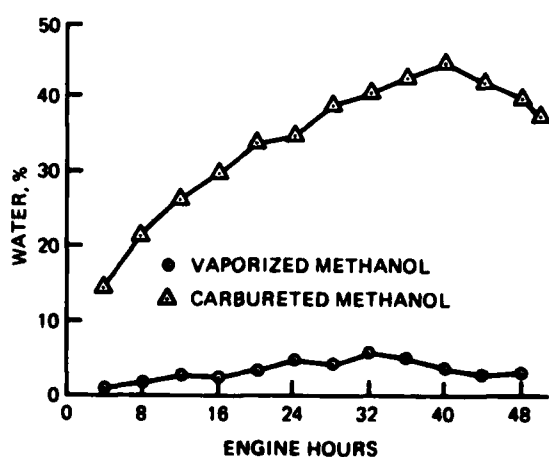
Fig. 18 – Water concentration
in lubricating oil
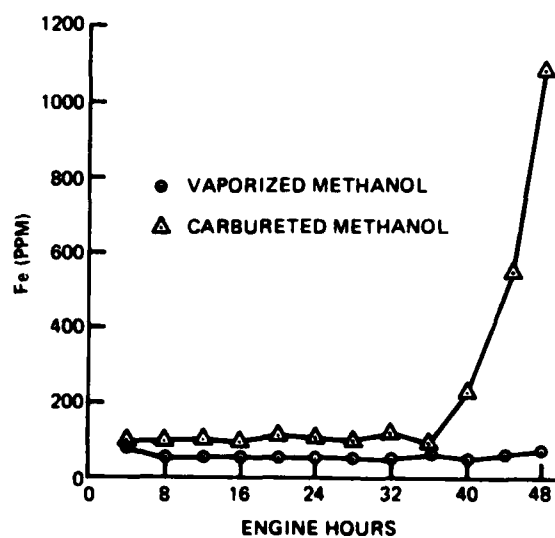
Fig. 19– Iron wear metals
concentration in lubricating
oil

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CONCLUSIONS

When evaluating these results, it must be realized that the test cycles used in this work were designed to correlate oil performance with field experience. This lab-to-field correlation may not exist when operating with varying fuels. The relevance of these tests can be verified only by conducting the types of field tests that were originally used during the test development. It appears that insufficient controlled methanol-fueled fleet testing has been conducted with the ambient and operational conditions necessary to validate or refute these results. Until such tests have been conducted, the conclusions drawn from this work should be viewed as indicators of possible field behavior.

These dynamometer tests indicate that the use of pure methanol as a fuel can result in large increases in engine wear and wear metal accumulation during low-temperature operating periods. This increased wear occurs primarily in the piston ring and upper cylinder bore area.

This increased wear caused by methanol does not appear to be accompanied by major irreversible degradation of the lubricant. However, the mechanism studies indicate that the lubricant does affect the wear rate. This lack of bulk oil degradation before the onset of wear implies that solutions to this wear problem are not achievable simply by increased additive treatment level or more frequent oil change intervals.

Methanol can also cause rust formation as well as wear. The extent of rust formation is dependent on the materials present and the metal and lubricant temperatures during engine operation. Therefore, this rusting phenomena would be design-dependent and vary in intensity from engine to engine. These engine test results, as currently obtained through wear metals measurements, appear to combine information on engine wear and nonrubbing area rust. This tends to complicate the analysis of the test results and may make development of solutions more difficult. Unfortunately, this engine test sequence does not appear to produce excessively high measured wear in short time spans with methanol.

The mechanism studies generally indicate that methanol or its intermediate combustion products directly attack the piston ring and cylinder bore area rather than first degrading the lubricant, although the mechanism of this direct attack is unclear at this time.

The blowby produced from methanol contains at least formaldehyde and formic acid. These materials are capable of causing corrosive attack within the ring zone, the area of highest concentration.

Ethanol, either by itself or blended with gasoline, does not appear to increase piston ring and cylinder bore wear in these tests.

RECOMMENDATIONS

The results obtained in these single-cylinder engine test need to be confirmed in both full-scale multicylinder laboratory engine tests and controlled field tests. Also, the engine operating conditions which promote this increased wear need to be thoroughly mapped so that valid estimates of the severity of the problem in actual field service can be made.

The alcohols used thus far in this program have been as pure as possible to isolate the actual alcohol effects. This purity level is unrealistic for actual fuels. The effects of other potential alcohol fuel components, particularly water, need to be investigated. A distinction should be drawn between wear in rubbing areas and metal removed by rusting in nonrubbing areas. Each of these problems should then be attacked separately.

More basic studies of the mechanisms by which methanol fuel results in increased engine wear need to be conducted. This information appears to be very important in developing effective lubricant solutions.

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APPENDIX A

CLR ENGINE TEST RESULTS SUMMARY

CLR ENGINE TEST RESULTS SUMMARY---TESTS 1 - 5

Test No.	1		2		3		4		5	
Test Cycle	IIC		IIC		VC		VC		VC	
Fuel	Unleaded		100% M		100% M		Unleaded		100% M	
Lubricant Code	A		A		A		A		A	
Test Duration, Hr	50		50		100		100		100	
Change in Ring End Gap, in.										
Top Piston Ring	0		0.002		0.002		0		0.002	
2nd Piston Ring	0		0.004		0.008		0.002		0.005	
3rd Piston Ring	ND		ND		ND		ND		ND	
Change in Rod Bearing	+0.0450		-0.0010		-0.1256		-0.0026		-0.0073	
Wear Metals, ppm										
Fe	50		120		462		51		500	
Cu	50		60		277		39		105	
Cr	50		50		5		5		17	

Viscosity, cSt	New	Used	New	Used	New	Used	New	Used	New	Used
40°C(100°F)	(69.3)	(39.0)	(69.3)	(120.4)	(69.3)	(53.5)	(69.3)	(45.4)	(69.3)	(57.0)
100°C(210°F)	(11.7)	(7.6)	(11.7)	---	(11.7)	(8.5)	(11.7)	(7.6)	(11.7)	(9.1)
TAN (D 664)	2.4	2.3	2.4	2.3	2.4	3.7	2.4	2.5	2.4	3.5
TBN (D 2896)	10.8	10.4	10.8	8.6	10.8	9.8	10.8	9.7	10.8	6.2
Pentane Insols/Coag, wt%		0.046		0.047		1.59		0.019		0.05
Benzene Insols/Coag, wt%		0.019		0.077		1.12		0.016		0.10
K.F. (H_2O), wt%		0.40		19.1		0.57		0.40		0.63

Lubricant Additives, wt% (new)	AL-6377-L	AL-6377-L	AL-6377-L	AL-6377-L	AL-6377-L
S	0.51	0.51	0.51	0.51	0.51
P	0.19	0.19	0.19	0.19	0.19
Ba	Nil	Nil	Nil	Nil	Nil
Ca	0.37	0.37	0.37	0.37	0.37
Mg	Nil	Nil	Nil	Nil	Nil
Zn	0.14	0.14	0.14	0.14	0.14
Notes		1	2,3		3
	Texaco	Texaco	Texaco	Texaco	Texaco
	ML-9 10W/30	ML-9 10W/30	ML-9 10W/30	ML-9 10W/30	ML-9 10W/30
Bore Wear (Top Only)	0.0005(0.0005)	---	0.0004(0.0004)	---	---

Notes:
1. At the end of test, lube contained 19.1% H_2O and 22.2% MeOH and formed yellow emulsion.
2. Hydraulic lifter sticking at 5.4 hr and 83 hr.
3. Piston pin seized in bushing.
4. Blowby diversion piston installed.
5. Exhaust valve stuck in guide.
6. Gelle cycle omitted from VC sequence.
7. At end of test, lube contained 25.1 H_2O and 8.4 MeOH and formed yellow emulsion.
8. Unusual wear metal trend, possible sampling problems.
9. At 383 hrs the idle cycle was extended to 135 minutes to try and increase wear.
10. Blowby and oil breather iron tube replace with stainless steel.
11. Piston was scuffed on 4 edges (bad piston).

CLR ENGINE TEST RESULTS SUMMARY—TESTS 6 - 12

Test No.	6		7		8		9		12	
				Oil Gallery Temperature Changed			9		12	
Test Cycle	VC		VC		IIC		VC		VC	
Fuel	100% M		Unleaded		15% M		100% M		100% M	
Lubricant Code	A		A		A		A		A	
Test Duration, Hr	100		100		50		100		100	
Change in Ring End Gap, in.										
Top Piston Ring	0.002		0.003		0		0.001		0.004	
2nd Piston Ring	0.004		0.003		0.006		0.004		0.005	
3rd Piston Ring	ND		ND		ND		ND		ND	
Change in Rod Bearing	~0.0009		-0.0089		-0.0024		-0.0104		~1147	
Wear Metals, ppm										
Fe	750		99		3		---		472	
Cu	203		53		1		---		74	
Cr	13		6		1		---		38	
Viscosity, cSt	New	Used	New	Used	New	Used	New	Used	New	Used
40°C(100°F)	(69.3)	(55.0)	(69.3)	(24.0)	(69.3)	(41.2)	(69.3)	(58.8)	63.5	62.8
100°C(210°F)	(11.7)	(8.7)	(11.7)	(5.3)	(11.7)	(7.8)	(11.7)	Boiled	11.4	7.6
TAN (D 664)	2.4	4.4	2.4	2.1	2.4	1.9	2.4	---	2.4	2.5
TBN (D 2896)	10.8	8.0	10.8	8.0	10.8	10.5	10.8	---	10.8	4.4
Pentane Insols/Coag, wt%		0.31		0.038		0.03		0.50		0.15
Benzene Insols/Coag, wt%		0.23		0.030		0.03		0.48		0.12
K.F. (H$_2$O), wt%		0.37		0.50		0.63		0.20		0.56
Lubricant Additives, wt% (new)	AL-6377-L		AL-6377-L		AL-6377-L		AL-6377-L		AL-7161-L	
S	0.51		0.51		0.51		0.51		0.53	
P	0.19		0.19		0.19		0.19		0.19	
Ba	Nil		Nil		Nil		Nil		Nil	
Ca	0.37		0.37		0.37		0.37		0.37	
Mg	Nil		Nil		Nil		Nil		Nil	
Zn	0.14		0.14		0.14		0.14		0.14	
Notes	3,5						4			
	Texaco		Texaco		Texaco		Texaco		Texaco	
	ML-9 10W/30		ML-9 10W/30		ML-9 10W/30		ML-9 10W/30		ML-9 10W/30	
Bore Wear (Top Only)	0.001(0.00015)		0.0002(0.0002)		0.00003(0.0005)		0.0003(0.0005)		0.00025(0.0003)	

Notes:
1. At the end of test, lube contained 19.1% H$_2$O and 22.2% MeOH and formed yellow emulsion.
2. Hydraulic lifter sticking at 5.4 hr and 83 hr.
3. Piston pin seized in bushing.
4. Blowby diversion piston installed.
5. Exhaust valve stuck in guide.
6. Gelle cycle omitted from VC sequence.
7. At end of test, lube contained 25.1 H$_2$O and 8.4 MeOH and formed yellow emulsion.
8. Unusual wear metal trend, possible sampling problems.
9. At 383 hrs the idle cycle was extended to 135 minutes to try and increase wear.
10. Blowby and oil breather iron tube replace with stainless steel.
11. Piston was scuffed on 4 edges (bad piston).

CLR ENGINE TEST RESULTS SUMMARY---TESTS 13 - 17

Test No.	13		14		15		16		17	
Test Cycle	VC		*		VC		VC		IIC	
Fuel	100% M		100% M		100% M		Unleaded		100% M	
Lubricant Code	A		A		B		A		B	
Test Duration, Hr	100		100		100		100		50	
Change in Ring End Gap, in.										
Top Piston Ring	0.000		0.001		0.003		0.002		0.001	
2nd Piston Ring	0.005		0.003		0.005		Broken		0.003	
3rd Piston Ring	ND		ND		ND		ND		ND	
Change in Rod Bearing	+0.0007		-0.0025		-0.0150		-0.0049		+0.0005	
Wear Metals, ppm										
Fe	477		177		133		22		149	
Cu	91		47		67		15		10	
Cr	8		21		13		Nil		Nil	

Viscosity, cSt	New	Used	New	Used	New	Used	New	Used	New	Used
40°C(100°F)	63.5	55.5	63.5	55.8	71.8	65.7	63.5	39.4	71.8	202.1
100°C(210°F)	11.4	9.2	11.4	9.2	11.0	10.2	11.4	7.6	11.0	—
TAN (D 664)	2.4	2.5	2.4	3.5	1.7	2.5	2.4	2.3	3.3	2.7
TBN (D 2896)	10.8	3.1	10.8	3.1	8.3	8.8	10.8	10.2	7.4	6.3
Pentane Insols/Coag, wt%		0.18		0.08		0.26		0.08		—
Benzene Insols/Coag, wt%		0.15		0.03		0.21		0.06		—
K.F. (H_2O), wt%		0.25		0.13		0.34		0.73		25.1

Lubricant Additives, wt% (new)	AL-7161-L		AL-7161-L		AL-7339-L		AL-7161-L		AL-7339-L	
S	0.53		0.53		0.36		0.53		0.36	
P	0.19		0.19		0.14		0.19		0.14	
Ba	Nil		Nil		Nil		Nil		Nil	
Ca	0.37		0.37		Nil		0.37		Nil	
Mg	Nil		Nil		0.114		Nil		0.114	
Zn	0.14		0.14		0.18		0.14		0.18	
Notes			6						7	
	Texaco		Texaco		Sunoco		Texaco		Sunoco	
	ML-9 10W/30		ML-9 10W/30		X892-79		ML-9 10W/30		X892-79	
Bore Wear (Top Only)	0.0002(0.0003)		0.00026(0.00035)		0.0000(0.0000)					

Notes:
1. At the end of test, lube contained 19.1% H_2O and 22.2% MeOH and formed yellow emulsion.
2. Hydraulic lifter sticking at 5.4 hr and 83 hr.
3. Piston pin seized in bushing.
4. Blowby diversion piston installed.
5. Exhaust valve stuck in guide.
6. Galle cycle omitted from VC sequence.
7. At end of test, lube contained 25.1 H_2O and 8.4 MeOH and formed yellow emulsion.
8. Unusual wear metal trend, possible sampling problems.
9. At 303 hrs the idle cycle was extended to 135 minutes to try and increase wear.
10. Blowby and oil breather iron tube replace with stainless steel.
11. Piston was scuffed on 4 edges (bad piston).

CLR ENGINE TEST RESULTS SUMMARY---TESTS 18 - 22

Test No.	18		19		20		21		22	
Test Cycle	VC		VC		VC		VC		VC	
Fuel	100% M		Unleaded		15% M		Unleaded		15% Eth	
Lubricant Code	C		B		A		A		A	
Test Duration, Hr	100		100		240		240		240	
Change in Ring End Gap, in.										
Top Piston Ring	0		0.001		0.003		0.003		0.002	
2nd Piston Ring	0.005		0.003		0.004		0.005		0.005	
3rd Piston Ring	0.010		0.002		0.009		0.008		0.007	
Change in Rod Bearing	−0.0047		−0.0016		−0.0054		−0.0037		−0.0122	
Wear Metals, ppm										
Fe	800		33		118		74		78	
Cu	170		35		60		44		41	
Cr	10		10		Nil		Nil		Nil	
Viscosity, cSt	New	Used	New	Used	New	Used	New	Used	New	Used
40°C(100°F)	67.7	20.3	71.8	24.3	63.5	41.8	63.5	41.9	63.5	47.4
100°C(210°F)	10.4	21.1	11.0	24.6	11.4	8.3	11.4	9.6	11.4	8.9
TAN (D 664)	2.7	3.1	3.3	3.5	2.4	4.5	2.4	5.3	2.4	3.6
TBN (D 2896)	6.3	1.9	7.4	6.3	10.9	8.9	10.9	10.1	10.9	9.1
Pentane Insols/Coag, wt%		0.14		0.12		0.02		0.01		0.03
Benzene Insols/Coag, wt%		0.08		0.05		0.01		0.002		0.02
K.F. (H$_2$O), wt%		0.22		0.15		0.15		0.14		0.37
Lubricant Additives, wt% (new)	AL-7320-L		AL-7339-L		AL-7161-L		AL-7161-L		AL-7161-L	
S	0.37		0.36		0.53		0.53		0.53	
P	0.14		0.14		0.19		0.19		0.19	
Ba	Nil		Nil		Nil		Nil		Nil	
Ca	0.23		Nil		0.37		0.37		0.37	
Mg	Nil		0.114		Nil		Nil		Nil	
Zn	0.15		0.18		0.14		0.14		0.14	
Notes	Lubrizoil 38364		Sunoco X892-79		Texaco ML-9 10W/30		Texaco ML-9 10W/30		Texaco ML-9 10W/30	
Bore Wear (Top Only)	0.0000(0.00004)		0.0000(0.00005)		0.0002(0.0002)		0.0002(0.0002)		0.0001(0.0001)	

Notes: 1. At the end of test, lube contained 19.1% H$_2$O and 22.2% MeOH and formed yellow emulsion.
2. Hydraulic lifter sticking at 5.4 hr and 83 hr.
3. Piston pin seized in bushing.
4. Blowby diversion piston installed.
5. Exhaust valve stuck in guide.
6. Galle cycle omitted from VC sequence.
7. At end of test, lube contained 25.1 H$_2$O and 8.4 MeOH and formed yellow emulsion.
8. Unusual wear metal trend, possible sampling problems.
9. At 383 hrs the idle cycle was extended to 135 minutes to try and increase wear.
10. Blowby and oil breather iron tube replace with stainless steel.
11. Piston was scuffed on 4 edges (bad piston).

CLR ENGINE TEST RESULTS SUMMARY---TESTS 23 - 27-1

Test No.	23		24		25		26-Common Sump Eng 1	Eng 2	27-1	
Test Cycle	VC		VC		VC		VC	VC	VC	
Fuel	15% Eth		100% E		100% M		100%M	Unleaded	100% M	
Lubricant Code	D		A		E		A	A	F	
Test Duration, Hr	240		100		100		462	462	100	
Change in Ring End Gap, in.										
Top Piston Ring	0.001		0.003		0.002		0.006	0.002	0.006	
2nd Piston Ring	0.003		0.004		0.008		0.008	0.003	0.008	
3rd Piston Ring	0.004		0.005		0.		0.018	0.010	0.013	
Change in Rod Bearing	-0.0012		-0.0015		-0.0013		-0.0070	-0.0113	0.0075	
Wear Metals, ppm									XRF	AA
Fe	84		62		176		553	553	1336	1225
Cu	56		77		21		81	81	52	45
Cr	Nil		Nil		Nil		Nil	Nil	45	23
Viscosity, cSt	New	Used	New	Used	New	Used	New	Used	New	Used
40°C(100°F)	67.5	47.5	63.5	54.7	29.4	28.5	63.5	46.3	106.0	107.4
100°C(210°F)	11.2	8.4	11.4	9.4	6.2	6.2	11.4	8.1	11.8	11.9
TAN (D 664)	2.5	3.3	2.4	2.8	0.2	0.8	2.4	20.7	2.0	6.0
TBN (D 2896)	7.9	6.6	10.9	7.8	7.8	2.2	10.9		10.7	
Pentane Insols/Coag, wt%		1.51		0.03		---		0.09		0.94
Benzene Insols/Coag, wt%		0.64		0.03		---		0.06		0.63
K.F. (H_2O), wt%		---		---		---		0.28		0.36
Lubricant Additives, wt% (new)	AL-7295-L		AL-7161-L		AL-5075-L		AL-7161-L		AL-7326-L	
S	0.40		0.53		0.05		0.53		0.23	
P	0.11		0.19		0.01		0.19		0.08	
Ba	Nil		Nil		0.84		Nil		0.0025	
Ca	0.09		0.37		0.01		0.37		0.35	
Mg	0.12		Nil		ND		Nil		Nil	
Zn	0.12		0.14		0.01		0.14		0.13	
Notes							9			
	Conoco		Texaco		MIL-L-46167		Texaco		MIL-L-21260B	
	Tracon		ML-9 10W/30		Arctic 5W/20		ML-9 10W/30		Preservative	
Bore Wear (Top Only)	0.0001(0.0002)		0.0002(0.00025)		0.0001(0.0001)		0.0004	0.0000	0.0000	

Notes:
1. At the end of test, lube contained 19.1% H_2O and 22.2% MeOH and formed yellow emulsion.
2. Hydraulic lifter sticking at 5.4 hr and 83 hr.
3. Piston pin seized in bushing.
4. Blowby diversion piston installed.
5. Exhaust valve stuck in guide.
6. Galls cycle omitted from VC sequence.
7. At end of test, lube contained 25.1 H_2O and 8.4 MeOH and formed yellow emulsion.
8. Unusual wear metal trend, possible sampling problems.
9. At 383 hrs the idle cycle was extended to 135 minutes to try and increase wear.
10. Blowby and oil breather iron tube replace with stainless steel.
11. Piston was scuffed on 4 edges (bad piston).

CLR ENGINE TEST RESULTS SUMMARY---TESTS 28-2 - 32

Test No.	28-2		29-2		30-1		31-1		32-	
Test Cycle	VC		VC		VC		VC		VC	
Fuel	100% M		Unleaded		100% M		100% M		100% M	
Lubricant Code	D		A		A		A		A	
Test Duration, Hr	100		100		100		152		100	
Change in Ring End Gap, in.										
Top Piston Ring	0.017		0.002		0.003		0.002		0.002	
2nd Piston Ring	0.010		0.004		0.005		0.008		0.004	
3rd Piston Ring	0.017		0.001		0.010		0.013		0.010	
Change in Rod Bearing	0.0095 Loss		-0.0085 Loss		-0.0227		+0.0032		-9.0068	
Wear Metals, ppm	XRF	AA	XRF	AA	XRF	AA	XRF	AA	XRF	AA
Fe	1543	1500	90	47	2126	2300	402	400	320	285
Cu	194	180	67	51	124	125	50	47	41	32
Cr	93	63	---	2	---	8	---	3	---	1
Viscosity, cSt	New	Used	New	Used	New	Used	New	Used	New	Used
40°C(100°F)	67.5	60.3	63.5	37.7	63.5	49.8	63.5	52.7	63.5	53.1
100°C(210°F)	11.2	9.8	11.4	7.6	11.4	8.8	11.4	9.2	11.4	9.2
TAN (D 664)	2.5	8.2	2.4	2.6	2.4	4.6	2.4	3.2	2.4	3.2
TBN (D 2896)	7.9	0.05	10.7	3.0	10.7	1.3	10.7	2.6	10.7	4.7
Pentane Insols/Coag, wt%		0.35		0.06		0.74		0.22		0.23
Benzene Insols/Coag, wt%		0.13		0.04		0.25		(0.19)		0.22
K.F. (H_2O), wt%		0.46		0.17		0.36		0.23		0.4
Lubricant Additives, wt% (new)	AL-7295-L		AL-7161-L		AL-7161-L		AL-7161-L		AL-7161-L	
S	0.40		0.53		0.53		0.53		0.53	
P	0.11		0.19		0.19		0.19		0.19	
Ba	Nil		Nil		Nil		Nil		Nil	
Ca	0.09		0.37		0.37		0.37		0.37	
Mg	0.12		Nil		Nil		Nil		Nil	
Zn	0.12		0.14		0.14		0.14		0.14	
Notes							10, 11		10	
	Conoco		Texaco		Texaco		Texaco		Texaco	
	Tracon		ML-9 10W/30		ML-9 10W/30		ML-9 10W/30		ML-9 10W/30	
Bore Wear (Top Only)	0.0006		0.0000		0.0000		---		0.00017	

Notes:
1. At the end of test, lube contained 19.1% H_2O and 22.2% MeOH and formed yellow emulsion.
2. Hydraulic lifter sticking at 5.4 hr and 83 hr.
3. Piston pin seized in bushing.
4. Blowby diversion piston installed.
5. Exhaust valve stuck in guide.
6. Galle cycle omitted from VC sequence.
7. At end of test, lube contained 25.1 H_2O and 8.4 MeOH and formed yellow emulsion.
8. Unusual wear metal trend, possible sampling problems.
9. At 383 hrs the idle cycle was extended to 135 minutes to try and increase wear.
10. Blowby and oil breather iron tube replace with stainless steel.
11. Piston was scuffed on 4 edges (bad piston).

CLR ENGINE TEST RESULTS SUMMARY---TESTS 33 - 38

Test No.	33		34		35		36		37		38	
Test Cycle	VC		VC		VC		VC		VC		VC	
Fuel	100% M		100% M		100% M		Phillips J		100% M		100% M	
Lubricant Code	D		A-1		F		A-1		A-1 + Zinc		H	
Test Duration, Hr	100		100		100		100		100		100	
Change in Ring End Gap, in.												
Top Piston Ring	0.002		0.000		0.000		0.002		0.003		0.003	
2nd Piston Ring	0.003		0.003		0.004		0.004		0.006		0.007	
3rd Piston Ring	0.005		0.004		0.006		0.008		0.010		0.016	
Change in Rod Bearing	-0.0022		-0.0113		-0.0080		+0.0024		-0.0051		-0.0235	
Wear Metals, ppm	XRF	AA	XRF	AA	XRF	AA	XRF	AA	XRF	AA	XRF	AA
Fe	524	494	316	322	103	75	49	39	208	195	432	338
Cu	70	44	68	49	38	20	33	16	62	40	67	71
Cr	---	4	16	2	---	1	---	2	---	3	---	3
Viscosity, cSt	New	Used	New	Used	New	Used	New	Used	New	Used	New	Used
40°C(100°F)	67.5	57.6	68.9	59.1	106.0	106.0	68.9	43.7	71.8	62.7	56.03	50.7
100°C(210°F)	11.2	9.5	11.7	9.7	11.8	11.4	11.7	8.1	11.8	9.96	9.95	9.1
TAN (D 664)	2.5	2.7	2.5	2.9	2.0	2.29	2.5	2.13	2.4	2.95	3.0	3.2
TBN (D 2896)	7.9	3.1	9.7	2.4	10.7	4.02	9.7	4.18	8.0	2.58	7.1	1.74
Pentane Insols/Coag, wt%		0.08		0.20		0.44		0.07		0.66		0.05
Benzene Insols/Coag, wt%		0.07		0.18		0.40		0.07		0.61		0.05
K.F. (H_2O), wt%		0.19		0.25		0.15		0.48		0.50		0.28
Lubricant Additives, wt% (new)	AL-7295-L		AL-8932-L		AL-7326-L		AL-8932-L		AL-9092-L		AL-8524-L	
S	0.40		---		0.23		---				0.33	
P	0.21		0.16		0.08		0.16		0.17		0.13	
Ba	Nil		---		Nil		---		---		Nil	
Ca	0.09		0.37		0.35		0.37		0.37		0.24	
Mg	0.12		Nil		Nil		Nil		---		Nil	
Zn	0.12		0.146		(0.13)		0.146		0.185		0.14	
Notes	10		10		10		10		10		10	
	Conoco		Texaco		MIL-L-21260B		Texaco		A+F Zinc		Mobil	
	Tracon		ML-9 10W/30		Preservative		ML-9 10W/30		Additive		Delvac-1	
Bore Wear (Top Only)	0.00007		0.00018		0.0001		0.00003		0.00018		0.00025	

Notes:
1. At the end of test, lube contained 19.1% H_2O and 22.2% MeOH and formed yellow emulsion.
2. Hydraulic lifter sticking at 5.4 hr and 83 hr.
3. Piston pin seized in bushing.
4. Blowby diversion piston installed.
5. Exhaust valve stuck in guide.
6. Golle cycle omitted from VC sequence.
7. At end of test, lube contained 25.1 H_2O and 8.4 MeOH and formed yellow emulsion.
8. Unusual wear metal trend, possible sampling problems.
9. At 383 hrs the idle cycle was extended to 135 minutes to try and increase wear.
10. Blowby and oil breather iron tube replace with stainless steel.
11. Piston was scuffed on 4 edges (bad piston).

REFERENCE SEQUENCE IIC TEST METHOD

REFERENCE SEQUENCE IIC TEST METHOD

November, 1971

1. SCOPE

This method describes an engine test procedure for evaluating the rusting and corrosion characteristics of motor oils. Information Letters are periodically published by General Motors [1] to provide additional new information pertaining to the test procedure.

2. SUMMARY OF METHOD

Prior to each test run, the engine is completely disassembled, solvent-cleaned, measured, and rebuilt in strict accordance with furnished specifications. Following this preparation, the engine is installed on a dynamometer test stand equipped with the appropriate accessories for controlling speed, load, and other various engine-operating conditions. The engine is operated continuously for 28 hours under conditions of moderate engine speed, partially warmed-up jacket coolant temperature, and rich air-fuel ratio. An additional 2 hours of operation at a slightly elevated jacket coolant temperature, all other conditions remaining unchanged are required. After 30 hours of operation (28+2), the engine is shut down for 30 minutes.

Following a carburetor and spark plug change, and adjustment of certain cooling system controls, the engine is operated for an additional 2 hours, under conditions of relatively high engine speed and jacket coolant temperature, and lean air-fuel ratio. At the conclusion of the test, the engine is disassembled and visually inspected to determine the extent of rust and corrosion formed.

3. SIGNIFICANCE

3.1 Method

The test method was designed to relate particularly to short-trip service under typical winter conditions in the upper midwestern United States. The method is most useful in evaluating the rusting characteristics of motor oils under the above conditions. The field service rusting and Sequence IIC results, shown in Appendix A, illustrate the existing correlation of this test method. There is evidence, however, that other service conditions may significantly change an oil's rusting tendency.

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[1] Communications relating to the Sequence IIC test should be addressed to Research Laboratories, General Motors Corporation, Fuels & Lubricants Dept., 12 Mile & Mound Roads, Warren, Michigan, 48090, Attn: R.H. Kabel or N.A.Hunsted

3.2 Deposit Ratings

Rust ratings obtained from Sequence IIC tests indicate the tendency of an oil to permit the formation of rust and corrosion products which interfere with hydraulic valve lifter and other close tolerance parts as well as contribute to general wear problems.

3.3 Other Ratings

The usefulness of other performance data, such as wear, deposits, etc., from this method, have not been established.

3.4 Use

The test method is useful for motor oil specification acceptance.

3.5 Validity

The results are significant only when all details of the procedure are followed.

4. DEFINITIONS

See Glossary of STP 315F.

5. APPARATUS

5.1 Test Engine Configuration

The test engine [2] (see Appendix B) shall have a 425 in.^{3} displacement, a V-8 cylinder configuration, a compression ratio of 10.25:1, and equipped with a two-barrel carburetor. The engine is mounted on the test stand in a manner such that the carburetor mounting flange to intake manifold interface is horizontal.

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[2] A 1967 Oldsmobile engine, part number 396822, has been found satisfactory for this

purpose. Purchase orders, placed with an Oldsmobile dealer (for complete engines, short blocks, and other special parts) should contain the following statement, "engines to be used for oil test purposes", and directed to Order Department Supervisor, General Motors Parts Divn., 6060 Bristol Road, Flint, Michigan, 48554. Short blocks are designated under part number 396230.

___

Speed, rpm	1500 ± 20
Load, bhp	25 ± 2
Oil, to engine, after filter, deg. F	120 ± 2
Oil pump outlet, psi	50 ± 10
Coolant, jacket out, deg. F	110 ± 1
Coolant, jacket in, deg. F	105 ± 1
Coolant, jacket flow rate, gpm	60 ± 1
Coolant, crossover out, deg. F at gpm	109 ± 2 at 3.0 ± 5
Coolant, crossover pressure outlet, psi	2.5 ± 0.5
Coolant, breather tube out, deg. F at gpm	60 ± 2 at 3.0 ± 0.5
Coolant, rocker covers out, deg. F at gpm per cover	60 ± 2 at 1.5 ± 0.5
Coolant out, rocker cover pressure, psi	5.0 ± 0.5
Air-fuel ratio	13.0 ± 0.5
Carburetor, air temperature, deg. F	80 ± 2
Carburetor, air humidity, grains per lb. of dry air	80 ± 5
Carburetor, pressure, in. water	0.1 to 0.3
Blowby rate, cfm at 100 F and 29.7 in. Hg	0.8 ± 0.1
Intake manifold vacuum, in.Hg	18 ± 1.5
Exhaust back pressure, in. water	4 ± 1
Exhaust back pressure max. differential, in. water	0.2
Crankcase oil filler tube	removed and plugged

Count test time from the moment when all of the above test conditions are obtained. Following this 28-hour period of operation, operate the engine for 2 hours under the same conditions as above except for the following changes:

Coolant, jacket out, deg. F	120 ± 1
Coolant, jacket in, deg F	115 ± 1
Coolant, crossover out, deg.F	119 ± 2

Make the change from 110 to 120 F within 3 minutes. The 3 minutes are counted as test time at 120 F.

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10.2 Sequence IIC Termination

Following 30 hours of operation, shut down the engine for 30 minutes to make adjustments in cover coolant temperature, to change carburetors, and to install a new set of AC 44S spark plugs. Immediately following the 30-minute shutdown and without oil drain, operate the engine for 2 hours under the following high speed hot conditions:

Speed, rpm	3600 ± 20
Load, bhp	100 ± 2
Oil, into engine, after filter, all viscosities, deg. F	260 ± 2
Coolant, jacket out, deg. F	200 ± 2
jacket in, deg. F	190 ± 2
jacket flow rate, gpm	60 ± 1
Intake crossover out, deg F	197 ± 2
breather tube out, deg F at gpm	199 ± 2 at 3.0 ± 0.5
rocker cover out, deg. F at gpm	198 ± 2 at
per cover	1.5 ± 0.5
rocker cover pressure, psi	5.0 ± 0.5
Air-fuel ratio	16.5 ± 0.5
Carburetor, air temperature, deg. F	80 ± 2
air humidity, grains per lb of dry air	80 ± 5
Pressure, in.water	0.1 to 0.3
Blowby rate, cfm at 100 deg F and 29.7 in.Hg	2.2 ± 0.2
Intake manifold vacuum, in.Hg	11 ± 2.5
Exhaust back pressure, in.water	30 ± 2
Exhaust back pressure, max., differential, in. H$_2$0	0.2
Crankcase oil filler tube	removed and plugged

Test time is counted from the moment when all of the above conditions are obtained (15 to 30 minutes maximum are permitted for stabilization).

At 32 hours of test time, the engine is stopped (see Appendix E) and the test is terminated at this point.

SEQUENCE VC

1. SCOPE

This method describes an engine test procedure that evaluates crankcase motor oils with respect to sludge and varnish deposits produced by engine operation under a combination of low and midrange temperatures. This test also indicates the capacity of the oil to keep positive crankcase ventilation (PCV) valves clean and functioning properly. Information letters are published by Ford Motor Company* to provide additional new information pertaining to the test procedure.

2. SUMMARY OF METHOD

This method uses a "Sequence V-C Oil Test Engine and Parts Kit" obtained from Ford Motor Company.* The test engine is completely disassembled, cleaned, and rebuilt in a specified manner. It is then installed on a dynamometer test stand equipped with appropriate accessories for controlling speed, load, and other conditions. It is operated with certified MS-08 fuel in three stages.

During Stage I, the engine is operated for 120 minutes at high power output with moderate oil and water temperatures and a lean air/fuel ratio (A/F). Stage II operates for an additional 75 minutes at higher oil and water temperatures. During Stage III, the engine is operated for 45 minutes at low rpm, with low oil and water temperatures, and with a rich A/F. Four cycles each of four hours duration are run each day until 48 cycles (192 engine operating hours) are accumulated.

3. SIGNIFICANCE

3.1 Method

The test method simulates a combination of low speed, low temperature, "stop and go" city driving and moderate turnpike operation which promote sludge formation. Field service indicates that motor oils which give good ratings in this test perform satisfactorily with respect to engine cleanliness. Test reproducibility on reference oils, precision, and field correlation data are shown in Appendix H.

* Communications relating to this Sequence V-C test should be addressed to: Fuels and Lubricants Section, Fuel Sciences Department, Scientific Research Staff, FORD MOTOR COMPANY, P. O. Box 2053, Dearborn, Michigan 48121, Attention: R. J. McConnell or C. H. Ruof. For procurement of engine and parts, see Appendix A.

At the conclusion of the test, the engine is completely disassembled to determine the extent of wear, sludge, varnish, and valve deposits. In addition, clogging of the PCV valve and oil screen are determined.

Directions are also included for Multiple Sequence Tests where the engine is partially disassembled, inspected, reassembled, and run for an additional 48 or 96 cycles (see Section 13).

METHANOL-FUEL EFFECTS ON SPARK IGNITION LUBRICATION AND WEAR

TABLE I

OPERATING CONDITIONS DURING STAGES OF EACH CYCLE

CONDITION			STAGE		
			I	II	III
Time, Minutes			120	75	45
Speed, RPM			2500 ± 25	2500 ± 25	500 ± 25
Load, bhp			86.6 ± 1	86.6 ± 1	2.0 ± 0.5
Oil	Gallery Temp., °F		175 ± 2	200 ± 2	120 ± 2
	Pressure, psi		45 – 60	45 – 60	45 – 60
	Cooling Time, minutes, Max.		///////	///////	15
Water	Outlet, °F		135 ± 2	170 ± 2	115 ± 2
	ΔT (Out – In), °F		6 ± 3	6 ± 3	6 ± 3
Carb. Air	Temp., °F		80 ± 2	80 ± 2	85 ± 5
	Humidity, Grains/lb		80 ± 5	80 ± 5	80 ± 5
	Pressure, in. H₂O		0.2 ± .1	0.2 ± .1	0.2 ± .1
Intake Vacuum, in. Hg			4.5 – 6.5	4.5 – 6.5	17 – 20
Ignition Timing, °BTDC			26	26	6
Blowby, cfm			2.5 – 3.0	///////	///////
Exhaust Back Pressure, in. H₂O			8.0 – 12.0	8.0 – 12.0	0 – 3.0
Exhaust Gas Analysis	Cylinder 1	%O₂	///////	///////	0.7 max.
		%CO	///////	///////	6.5 ± 0.5
	Cylinder 5	%O₂	///////	///////	0.7 max.
		%CO	///////	///////	6.5 ± 0.5
	Left Bank	%O₂	1.8 ± 0.5	1.8 ± 0.5	///////
		%CO	0.5 max.	0.5 max.	///////
	Right Bank	%O₂	1.8 ± 0.5	1.8 ± 0.5	///////
		%CO	0.5 max.	0.5 max.	///////

Note: Operating conditions shown are intended to be mid-range values.

EXHAUST GAS CONCENTRATIONS AND AIR/FUEL RATIOS
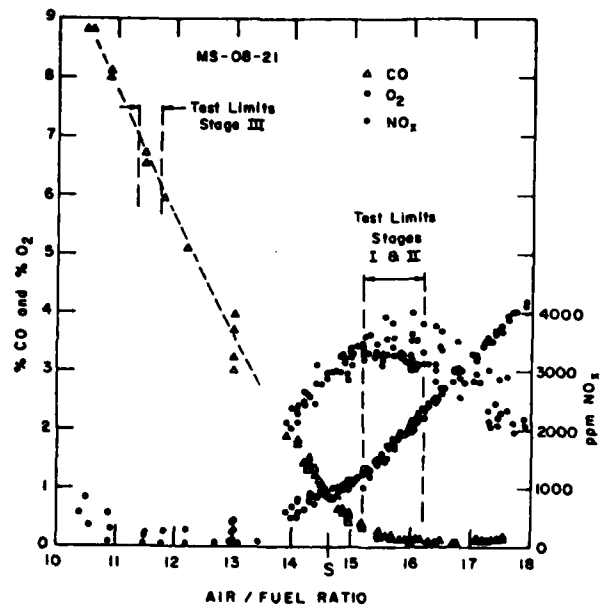
SEQUENCE VC (LEADED MS08) VERSUS
12,000-MILE FIELD TEST (UNLEADED AND LEADED)

Vehicle Test Conditions	Vehicle Gasoline
351 CID 2V	● Unleaded Gasoline
EGR	■ Same Plus 0.5 g Pb/Gal.
No Oil Drain	

Sludge Correlation Data — Seq. VC Sludge Rating vs Vehicle Sludge Rating

Varnish Correlation Data — Seq. VC Varnish Rating vs Vehicle Varnish Rating

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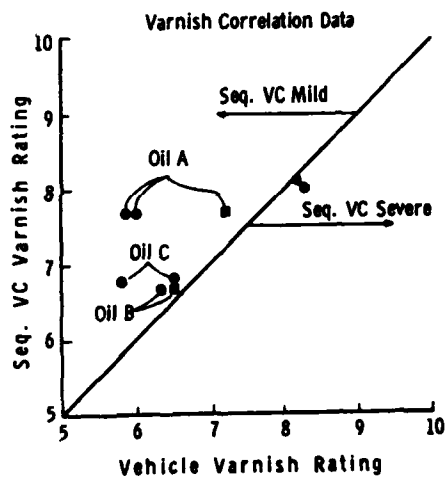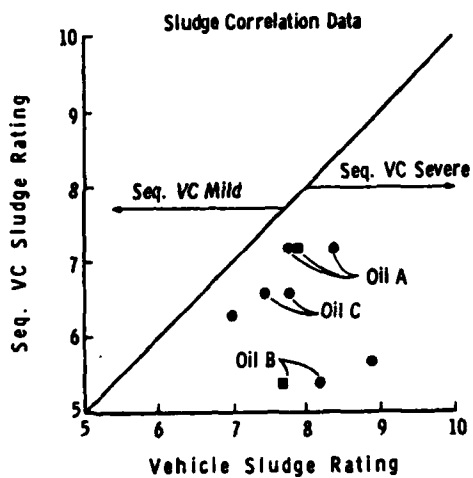   DAMA-ARZ (DR CHURCH)   1
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